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STRENGTH PROPERTIES OF SOME PACIFIC AND INDIAN OCEANS SEDIMENTS

By

D. G. Anderson

August 1971

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NAVAL CIVIL ENGINEERING LABORATORY
Port Hueneme, California 93043

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In addition to displaying graphical plots of sediment strength and index property variations with depth, the data suggest other important trends. For example, when the locations considered were divided into three physiographic provinces: continental terrace, abyssal plain, and abyssal hill, a considerable amount of data scatter was found to exist between similar provinces. Seafloor sediment provinces must be defined more precisely before it will be possible to categorize seafloor soil engineering properties on the basis of provinces.

Attempts were made to correlate the measured strength data with index properties of the sediments (Atterberg limits) that can be determined from disturbed or remolded samples. For the relatively shallow sediments considered in this study, no useful relationships were observed.

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INTRODUCTION

Subject and Purpose

This report presents the results of a sediment strength investigation conducted on core samples from 18 locations in the southwest Pacific and eastern Indian Oceans. The investigation was accomplished in two phases. The initial phase involved a series of shipboard vane shear tests, while the latter phase included the laboratory determination of sediment index properties and the correlation of these index properties to sediment vane shear strength. The latter stage also considered variations of sediment strength and index properties with respect to the depositional environment.

The contents of this report should be of interest to both the marine geologist and the soils engineer. Since sediments from the geographic areas involved in this study have received little attention from a soil mechanics standpoint, the variations in shear strength and index properties presented in the following pages may assist the marine geologist in defining important geologic events of the past. The type and frequency of the defined events such as turbidity currents at a given site, for example, will, it is hoped, indicate the variability of properties surrounding that site. The soils engineer, in turn, may utilize the techniques to perform foundation designs for inexpensive structures to be located at a particular site. If a geologic review finds that conditions are uniform in the area being considered, the engineer may, on a limited basis, extrapolate design information to areas adjacent to the site studied.

The latter engineering use of the data seems of particular value, since many inexpensive structures, that may be deployed in the future, cannot justify the time and expense associated with a detailed site investigation. However, when required, the soils engineer must still provide safe but cost-effective design recommendations. The information presented in this report will assist the soils engineer in fulfilling these requirements.

The purpose of this report is, therefore, to present soil shear strength data and index property information for these 18 locations in the southwest Pacific and eastern Indian Oceans. The data are presented with respect to established trends in soil behavior and to pertinent geologic characteristics of the areas.

Background

During the spring and summer of 1969, the author of this report accompanied scientists from NUC (Naval Undersea Research and Development Center), San Diego, on an extended oceanographic investigation of 18 areas in the southwest Pacific and eastern Indian Oceans. Each area belonged to one of the following three physiographic provinces: (1) continental terrace (shelf and slope), (2) abyssal plain, and (3) abyssal hill. These provinces formed sedimentary environments in which distinctive sediment types were apt to be found. The NUC scientists studied the environment of each area with respect to water chemistry, biologic activity, and sediment type. Studies were accomplished by employing such oceanographic tools as Nansen bottles, trawl nets, and gravity corers. Data obtained from bathythermographs, echograms, and subbottom profilers also helped establish the characteristics of the particular province.

While aboard ship, the author assisted several marine geologists in obtaining and classifying sediment samples from the site. The samples, which included red clays, oozes, and terrigenous silts and clays, typified the materials found in major troughs, basins, and plains of that geographic region. Within several hours of sampling the sediment, the author performed tests that measured the original and remolded vane shear strengths of sediment sections from various depth increments. The tests utilized a motorized vane shear apparatus to establish the undrained stress response during controlled conditions of strain.

Difficulties associated with performing other laboratory tests aboard ship prevented the immediate completion of the soil classification program; consequently, each sample was visually identified, labeled, and stored at 4 degrees Celsius (Centigrade) until the ship returned to the United States. Once the samples were received at NCEL (Naval Civil Engineering Laboratory) (about 6 months after obtaining the samples), a series of laboratory tests was performed on the cores to complete the engineering classification. These tests included the determination of the sample's water content, Atterberg limits, specific gravity, grain size distribution, and carbonate carbon and organic carbon contents.

Approach and Scope

This report summarizes the results of the shipboard vane shear test program and the subsequent series of laboratory identification tests. These results are presented after a brief summarization of the techniques involved in sampling the material, in performing the vane shear tests, and in identifying the samples. The initial portion of the report also considers the theory of vane shear tests and the cause of strength variations within the soil strength profile.

The results presented for each site include (1) a general description of the sediment environment, (2) the location of the samples in the soil profile, (3) the percentages of sand, silt, and clay, (4) the index properties, and (5) the vane shear strengths.

These data are then discussed with respect to relevant information on the seafloor environment (such as geomorphic characteristics of the site) and compared with results from sites which exhibit similar characteristics. Conclusions and recommendations complete the summary.

The scope of this report is limited to the presentation of vane shear strength data and sediment index properties and to a brief description of the geological characteristics at the sites.

SAMPLING AND TESTING PROCEDURES

The following three sections present general information concerning the procedures and types of equipment employed during sampling and testing. The first two sections, CORING and VANE SHEAR TESTING, review techniques utilized aboard ship; while the last section, INDEX PROPERTIES, concerns methods employed in the NCEL Seafloor Soil Mechanics Laboratory. This review is included because the results are presented for both engineers and geologists. Unfortunately engineers and geologists do not always use the same terminology. These sections will, it is hoped, eliminate some of the confusion which might otherwise arise.

Coring

Deep-water (greater than 100 fathoms) "undisturbed" sediment samples were obtained with gravity corers. Each corer consisted of a steel barrel with a plastic core liner, a finger-type sample retainer, and a cutting head. The length of the core barrels varied from 1.8 to 3 meters. The corers did not utilize pistons during sample recovery. Table 1 lists some of the corers' critical dimensions. Gravity corer A functioned as the primary sampling tool, while the trip corer acted as a weight for the trip mechanism. Gravity corer B was employed several times to verify the soil profile at a site.

Table 1. Corer Dimensions

Corer	Barrel Diameter BD (cm)	Outer Diameter of Cutting Head, OD (cm)	Inner Diameter of Cutting Head, ID (cm)	Area Ratio (%)
Gravity Corer A	7.3	7.9	6.7	39
Gravity Corer B	7.0	8.2	6.0	87
Trip Corer	7.6	8.2	6.7	50

Area ratios were determined from*

$$\text{Area ratio, } A_r \text{ (\%)} = 100 \left(\frac{OD^2 - ID^2}{ID^2} \right) \quad (1)$$

The area ratios are also tabulated in Table 1; however, these values do not include the effect of the sample retainer. The dimensions of the retainer suggest that values in Table 1 should be increased by approximately 10% to include this effect. The implications associated with such high area ratios are reviewed under DISCUSSION OF RESULTS - General.

The gravity corer was suspended from a tripping mechanism as it was lowered by a ship's cable. When the trip weight contacted the sediment surface, the gravity corer released, fell approximately 30 feet, and penetrated the bottom material. The corer utilized 500 pounds of lead weight to increase the depth of penetration. A pinger was attached above the tripping mechanism to monitor the position of the corer during the lowering process.

A short gravity corer functioned as the weight for the tripping mechanism. This trip corer (Table 1), similar in design to the larger gravity corer (plastic liner, core retainer, and cutting head), sampled the sediment about 3 feet from the point at which the gravity corer penetrated. The trip corer was 4 feet long and weighed approximately 70 pounds.

After the gravity corer penetrated the sediment, the winch line was used to pull the device slowly out of the bottom and to the water surface. When the apparatus reached the surface, the winch line was removed, the corer was disassembled, and the sediment sample was stacked in a vertical position. The length of samples from the deep-water site varied from 0 to 3 meters.

A similar procedure was used to obtain shallow-water sediment samples; however, the trip mechanism and pinger were not included in the operation. The lowering winch was allowed to freewheel during descent, thus achieving a near free fall condition. The length of cores obtained at the shallow-water sites also varied from 0 to 3 meters. The typical coring operation lasted from several minutes to an hour, depending upon the depth of the water at the site.

Vane Shear Testing

Within several hours of the coring operation, the author evaluated the original and remolded vane shear strengths of the sediment cores by using a Wykeham Farrance laboratory vane apparatus (Figure 1).

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* See foldout list of symbols after References.

This device rotated a vane embedded in the sediment at a constant rate of rotation. A calibrated spring mounted in the apparatus developed a torsional resistance to vane rotation that was semi-empirically related to the undrained strength of the soil.

The laboratory shear device, modified by NUC for shipboard use, employed an AC electric motor to rotate the vane at a rate of 23 degrees per minute. The four-bladed vane had a 1.25-centimeter diameter (D) and a 1.25-centimeter height (H). The height-to-diameter ratio (H/D) of the vane was, consequently, 1.0. During the strength test, a graduated dial on top of the vane shear apparatus displayed the degrees of torsional resistance corresponding to degrees of vane deflection (Figure 1).

The vane shear tests were conducted on various increments from each sediment core. The number of vane tests per core varied according to the amount of data necessary to establish a strength-versus-depth correlation; however, five or more test series were usually performed to define any strength-depth trends adequately.

The vane shear test procedure involved the following sequence of events: (1) the core length was sectioned, (2) the vane shear tests were conducted on the core section, and (3) the tested section was stored for later use. The Wykeham Farrance apparatus could only embed the vane 4 centimeters below the soil surface; therefore, the core length (liner with sample inside) was generally cut into 10-centimeter sections.

The test procedure varied slightly for the upper 10 to 13 centimeters of core, since this material generally exhibited very low shear strengths. To minimize the possibility of disturbance in this zone, the top portion of the core was tested before sectioning. The Wykeham Farrance apparatus had the capability of testing core increments from 0 to 1.0 meter long. When the length of the core exceeded 1.0 meter, the core was sectioned at a lower depth (1.0 meter from top) where the soil strength was considerably greater and, consequently, the danger of disturbance was less.

Each 10-centimeter sediment sample was tested at four depths. The first and second depths were achieved by inserting the vane into the top of the sectioned sample, while the third and fourth depths were attained by inverting the sample and forcing the vane into the sample's bottom. A distance of approximately one vane diameter separated the individual tests (Figure 2).

The vane shear tests at each depth consisted of original and remolded strength determinations. The original tests were conducted by rotating the vane in the undisturbed section of the sediment sample. The value of maximum stress displayed on the graduated dial corresponded to the "undisturbed" or original vane shear strength of the soil. The remolded strength determination involved rotating the vane several times to remold the soil in the failure zone, waiting 10 minutes, and again performing a stress-versus-strain determination. The maximum stress represented the remolded strength of the material.

As mentioned in the first two paragraphs, the torsional resistance of the spring to vane rotation was related to the strength of the soil. This interpretation was based upon the following equation:

$$T_F = \frac{\pi D^2 H}{2} \left(1 + \frac{D}{3H}\right) S \qquad (2)$$

where T_F = the failure torque (gm/cm)

D = vane diameter (cm)

H = vane height (cm)

S = vane shear strength (gm/cm^2)*

By applying the appropriate torque factors, the original and remolded vane shear strengths were calculated.

Difficulties associated with performing certain index property classification tests aboard ship prevented immediate completion of the soil test program; therefore, each sediment section was visually classified, labeled, and stored at 4 degrees Celsius in containers filled with seawater until they could be returned to the United States.

Index Properties

When the sediment samples arrived at NCEL, personnel from the Seafloor Soil Mechanics Laboratory performed a series of tests to define the sediment index properties. These laboratory tests included the determination of original water content, grain size distribution, specific gravity, carbonate carbon and organic carbon contents, and Atterberg limits.

The number of laboratory tests on each core varied. When the material within the core appeared homogeneous, a single representative sample was selected from the core for grain size, specific gravity, and carbonate carbon and organic carbon contents tests. If major variations (evidenced by change in color or noticeable change in grain size) were detected, a representative sample from each soil type was tested. The laboratory test program established the original water content and Atterberg limits at every interval upon which a vane shear test was performed.

The following paragraphs present a general review of the laboratory testing procedure. In most cases these procedures follow

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* S is considered to be approximately equal to the undrained shear strength of the soil, c.

standard engineering techniques; however, the nature of the material sometimes required deviations from accepted procedures.

Original water content. The original water content of the soil mass, defined as the weight of water in a portion of sample divided by the weight of solids in that portion, was established by oven-drying approximately 50 grams (dry weight) of sample at 105 degrees Celsius for approximately 24 hours. The 50-gram sample was selected from the 10-centimeter sediment section after the section had been thoroughly mixed.

Grain size distribution. The results of a sieve and hydrometer analysis were used to determine the sample's grain size distribution. The test procedure involved mixing 50 grams (dry weight) of sample from the sediment section with an electric mixer. During the mixing, 125 milliliters of diluted sodium pyrosphosphate were added to deflocculate the soil. After the slurry was mixed for approximately 1 minute, the contents were added to a 1,000-milliliter hydrometer jar. The hydrometer jar was then filled with distilled water and left overnight in a water bath at 20 degrees Celsius. The remainder of the hydrometer test followed standard American Society for Testing and Materials (ASTM, 1964) procedures. After the 24-hour hydrometer reading, the entire sample in the hydrometer was washed through a Number 325 sieve and was dried for 2 hours at 105 degrees Celsius, after which the material was shaken through a nest of sieves. A representative portion of the material coarser than the 325 sieve was saved. The Bureau of Soils Classification System was used to distinguish between sands, silts, and clays. This classification system considers the particle a sand if the grain size is between 2 and 0.05 millimeters, a silt if the grain size is between 0.05 and 0.005 millimeter, and a clay if the particle is smaller than 0.005 millimeter.

Carbonate-organic carbon content. The carbonate carbon and organic carbon contents of the samples were determined by utilizing a Leco induction furnace. The furnace measured the amount of carbon released during the combustion of two samples from a given increment. One sample was treated with hydrochloric acid to remove the carbonate carbon content, while the second sample was left untreated. The treated sample thus included the carbon from the organic matter only, and the untreated sample measured carbon from both. By subtracting one from the other, the amount of carbon lost during the reaction with the hydrochloric acid was defined; this amount was the carbon content from the carbonate source only. Since only the carbon was measured, instead of whole molecules of organic matter or carbonate which contain other elements, the organic carbon and carbonate carbon results reported should be multiplied by factors of 8.33 and 1.7, respectively, in order to obtain the weight percentages of the compounds.

The tests were performed on 1/2-gram samples which had been dried during the original water content determination and, subsequently, powdered. Tin-coated copper and iron chips were placed in the crucible to accelerate the reaction.

Specific gravity. An air comparison pycnometer was used for all specific gravity determinations. The pycnometer had two chambers (designated as measuring and reference) calibrated to a known volume. A known weight of oven-dried soil was subjected to a partial vacuum in the measuring chamber. At this pressure, the change in volume of the measuring chamber relative to the reference chamber represented the volume of solid particles. The volume of solids measured by this technique appears to be closely comparable to those measured by the accepted ASTM method (Hironaka, 1966).

Atterberg limits. The Atterberg limits determination included both liquid limit and plastic limit tests. The procedure for the plastic limit tests was similar to the accepted ASTM (1964) method. However, the samples were not air dried before testing. The simplified single-point analysis was used for the liquid limit determination (Lambe, 1951). The method was based on the assumption that the slope of the logarithmic plot of blows versus water content (also on log scale) was a straight line. If this assumption were correct, the liquid limit could be obtained from one point on the line. The following equation defines that relationship.

$$LL = w_n \left(\frac{n}{25}\right)^{0.121} \tag{3}$$

where LL = the liquid limit (%)

w_n = water content of the soil which closes in n blows in the standard liquid limit device (%)

n = number of blows to close the groove (between 22 and 28).

Miscellaneous

Several other index properties were determined on the basis of results from the aforementioned tests. The void ratio, defined as the volume of voids divided by the volume of solids, originated from the original water content determination. Equation 4 shows this relationship.

$$e = WG_s \tag{4}$$

where e = void ratio

W = water content

G_s = specific gravity of particles

The plasticity index (Equation 5) represented the difference between the liquid limit and the plastic limit, while the liquidity index (Equation 6) equalled the difference between the original water content and the plastic limit divided by the plasticity index.

$$PI = LL - PL \tag{5}$$

$$LI = \frac{W - PL}{PI} \tag{6}$$

where LI = the liquidity index

PL = the plastic limit

PI = the plasticity index

STRENGTH CONSIDERATIONS

The various classification systems generally distinguish between a cohesive and a cohesionless soil. This distinction arises because the factors affecting the strength of soils in each category differ. The strength of a cohesionless soil depends upon the soil's density, the particle angularity and shape, the particle size, and the particle gradation. The strength of a cohesive soil, in turn, is a function of the particle mineralogy, the particle size, the void ratio, the effective stress in the vertical and horizontal planes, and the soil's stress history. Since the two varieties of soils derive their strength by independent mechanisms, the criteria involved in evaluating the two soils for strength must differ.

Unfortunately, the vane shear device has been used to test both cohesive and cohesionless sediments. However, the device was designed to measure the undrained strength of cohesive soils. Even in this role, it has limitations which should be understood.

The first paragraph in this section also mentioned that the strength of a soil varies as certain sediment properties vary. In some cases, these changes correspond to alterations in the depositional environment. A few sentences are, therefore, devoted to the variation of strength with environmental conditions.

Vane Shear Strength

As discussed earlier, the shear strength profile of each core was established by utilizing a vane shear testing apparatus. Although the vane shear device has received almost universal acceptance as a tool for defining the undrained shear strength of cohesive soils, several theoretical limitations exist. In several instances, these limitations assist the reader in understanding the applicability of the results, while, in other cases, the limitations restrict the usefulness of the strength data.

The simple relationship between vane shear strength and torque is based upon several assumptions, which can be stated as follows (Skempton, 1948; Kenney and Sandva, 1965; Brand, 1967):

(1) The soil is purely cohesive ($\phi = 0$); no drainage takes place during shearing.

(2) The soil is homogeneous and isotropic.

(3) Insertion of the blade causes no disturbances.

(4) Shearing takes place by shearing over the surface of the cylinder generated by the rotating vane.

(5) No progressive failure takes place in the soil, and the shear strength is fully mobilized on the surface of the cylinder at failure.

The validity of these assumptions determines the significance of the test's results.

Theory assumes that the soil is purely cohesive. The consequence of a purely cohesive soil is essentially no drainage during the shearing process. The validity of the assumption depends upon the type of soil tested and the rate of vane rotation.

When the soil is not purely cohesive ($\phi = 0$), test results from the vane shear test become very difficult to interpret. Although certain individuals (Evans and Sherratt, 1948) have advanced expressions which account for a finite value of the angle of shear resistance (ϕ), none of these expressions have proved to be applicable to more than a few soil types with very low values of ϕ. When the angle of shear resistance does not equal zero, such factors as dilatancy during shearing and the mode of failure (failure ceases to take place along the bounds of a cylinder) must be considered (Brand, 1967).

For a particular cohesive material, Sridharan and Madhav (1964) found that the shape of the stress-strain curve depends upon the rate of strain. The strength increased with increasing strain rate while the strain at failure decreased. Sridharan and Madhav attribute

the changes to the rate of particle reorientation and the viscous effects of strength. Table 2 summarizes the results of studies by Sridharan and Madhav (1964), Carlson (1948), and Evans and Sherrat (1948).

Table 2. Torsional Moment Versus Rate of Rotation

Reference	Torsional Moment (%)		
	Rate of Rotation		
	2^{o}/min	6^{o}/min	30^{o}/min
Carlson	100	102	117
Evans and Sherrat			
W = 42.5*	100	116	156
W = 55.5	100	127	172
W = 61.0	100	120	200
Sridharan and Madhav			
Undisturbed	100	110	132
Remolded	100	108	118

* Where W = water content of soil (%)

Although the results are scattered, several apparent trends exist. The vane shear strength of the soil increases with increasing rate of rotation. The increase is generally greater for samples with higher water contents, and the increase is generally greater during the undisturbed test.

The torque at failure is the sum of the opposing torques on the cylinder side and on the two cylinder ends:

$$T_{Failure} = T_{Sides} + T_{Ends} \tag{7}$$

Equation 2 (vane shear testing) reflects this information if the shear strength on the horizontal surface equals the shear strength on the vertical surface.

$$T_F = 1/2\ \pi\ D^2 H\ S_V + 1/2\ \frac{\pi D^3}{3}\ S_H \qquad (8)$$

If $S_V = S_H = S$

$$T_F = \frac{\pi\ D^2 H}{2}\ (1 + \frac{D}{3H})\ S \qquad (2)$$

$$\text{or } S = \frac{2T_F}{\pi\ D^2 H\ (1 + \frac{D}{3H})}$$

Aas (1965) used vanes of different D/H ratios to determine the ratio of the shear strength on the horizontal surface, S_H, to the shear strength on the vertical surface, S_V. Results indicated that the ratio S_H/S_V varied from 1.1 where the cohesive material was slightly overconsolidated to 1.5 and 2.0 when the material was normally consolidated. In the most severe condition, the assumption that the strengths in both planes are equal could overestimate the strength in the vertical plane by approximately 20%. In the top few meters of sediment, S_H should be nearly equal to S_V.

When the blade is inserted into the soil, the soil around the vane is, to some extent, disturbed and weakened (Gray, 1957). Aas (1965) found that if the vane is left one day after penetration, an increase in strength occurs. The increase was attributed to a dissipation of pore pressures set up during vane penetration. For Aas's tests, the average ratio between the conventional and the delayed vane tests varied from 1.28 to 1.52, the greatest value being found for the vane having the greatest H/D ratio. Unfortunately, delaying each test would consume excessive testing time.

The failure surface during the vane shear test is assumed to occur along a circular cylindrical surface with a height, H, and a diameter, D. Gibbs (1960) shows that at larger rotational strains failure occurs on such a surface. However, Skempton (1948) suggests that the failure surface need not necessarily be tangential to the vane blades but might be located some distance from them. In this case, the size of the cylinder would be greater than indicated in Equation 2; consequently, the actual vane strength would be less.

Brand (1967) considers the effect of incomplete stress mobilization. If such conditions exist, the shear stress varies over the cylinder ends. For H = D, the effect may decrease the measured torque by approximately 4%. Brand (1967) believes that such conditions may occur if failure takes place at relatively high strain.

The net results of all these departures are summarized in Table 3. The table also indicates the magnitude of the effect.

Table 3. Summary of Factors Affecting Vane Shear Strength

Factor	$S_R = \frac{\text{Measured Vane Strength}}{\text{Actual Undrained Strength}}$	Magnitude of Problem in Seafloor Strength Measurements
Finite value for angle of shear resistance ($\phi = 0$)	$S_R > 1.0$	Important
Rate of rotation greater than 6^o/min	$S_R > 1.0$ (assuming strength at 6^o/min equals actual)	Important
Anisotropic soils ($S_H > S_V$)	$S_R > 1.0$ (for S_V) $S_R < 1.0$ (for S_H)	Small
Vane insertion	$S_R > 1.0$	Moderate
Enlarged failure surface	$S_R > 1.0$	Moderate
Incomplete stress mobilization	$S_R < 1.0$	Moderate

Since the number of studies conducted on the vane shear testing device is limited, no quantitative magnitude can be placed on the factors influencing strength. Empirical evidence suggests, however, that the results of the vane shear test provide a good indication of the undrained strength of cohesive soils. The results tend to be greater than results obtained by unconfined compression (Gray, 1957) but compare well with in-situ failure evaluations (Carlson, 1948) and consolidated undrained tests (Lea and Benedict, 1952).

Geologic Controls

The introductory paragraphs to this section discuss some of the parameters affecting the strengths of cohesive and cohesionless soils. Although the various parameters owe their existence to a number of independent processes, the environment of a region generally defines the conditions at a site. This dependency is even more pronounced in the oceans of the world. Air and water currents generally control the distribution of terrigenous materials, while temperature, depth, and geomorphology determine the location of pelagic material. Since the vane shear strengths depend upon the degree of soil cohesiveness ($\phi \rightarrow 0$), the following discussion considers the soil as either cohesive or cohesionless. The cohesionless category therefore includes both terrigenous and pelagic materials. The cohesive subdivision follows a similar procedure by considering fine silts and clays of terrigenous origin and oozes and red clays of pelagic origin.

Cohesionless materials abound in shallow-water areas. Ocean and long-shore currents transport these materials from river deltas, coral reefs, etc. to a variety of locations. However, the size of cohesionless material is such that a large amount of energy is necessary for transportation. This requirement restricts most movement to near-shore regions and to constricted channels with high current velocities. Cohesionless materials occur in the deep ocean as turbidities (that have been transported from shallow-water coastal zones) and authigenic accretions. The turbidities are particularly prevalent near the base of the continental slopes. Whether the cohesionless material is in shallow or deep water, the soil strength depends upon basically the same parameters. Unfortunately, the vane shear device cannot adequately correlate these parameters to some form of strength measurement.

Cohesive materials are found on the continental shelf near river deltas and areas of low current activity and on the floor of the deep ocean. Since the strength of the cohesive material varies with mineralogy, particle size, void ratio, stress distribution, and stress history, a wide range of strengths might be expected on the seafloor. As currents change, the depositional pattern changes. Periods of low deposition may result in soils which exhibit higher strengths (because of secondary time effects) or lower strengths (remolding by benthic organisms for example) than might be anticipated. These alterations, in turn, cause variations in the strength-versus-depth profile. The type of material deposited may also change. As the continental environment changes, the amount of illite, kaolinite, montmorillonite volcanic debris, or marine life varies. In final form, the change is again reflected by variations in the shear strength profile. The environmental change may also alter the deposition of pelagic material. Some pelagic materials exhibit unusual strength characteristics believed to be related to their composition. These characteristics often result in unique strength profiles. In some cases, the stress history of the soil changes. If bottom currents erode the surface sediments, a severe

discontinuity may appear on subsequent strength profiles. The same effect may occur when the site has been above sea level for a time interval.

A vane shear strength evaluation can, therefore, detect the variations in the strength profile (for cohesive soils) associated with changes in the geologic realm. However, a careful mineralogic and geologic investigation is usually necessary to correlate the specific occurrence with the strength variation.

RESULTS

The results of the vane shear and laboratory test programs are presented in Table 4. Each result indicates the particular result considered most representative for the entire sediment section. In several instances, tests such as grain size, carbon content, and specific gravity were not performed on a given section. A dash in the tabulated data reflects this condition. Although four vane shear tests were usually conducted on a sample section, the results show a single value for the entire section. This value represents the average of the vane strength measurement in the sample section.

The general sediment environment was defined after reviewing articles (see DISCUSSION OF RESULTS) in various geological journals and conversing with several marine geologists (Hamilton, 1970; Dill, 1970).

Station	General Sediment Environment	Sediment Depth (cm)	% Sand	% Silt	% Clay	Carbonate Carbon/ Organic Carbon Content (%)	Orig Wate Cont W
A	Abyssal	72 - 82	5	29	66	2.12/0.01	20
	Hill	192 - 202	-	-	-	-	22
	Abyssal	10 - 20	-	-	-	-	32
B	Hill	111 - 121	11	22	67	-/0.18	28
		224 - 234	-	-	-	-	29
C	Abyssal	12 - 22	9	30	61	1.28/0.11	16
	Hill	156 - 166	-	-	-	-	17
	Abyssal	0 - 10	-	-	-	-	23
D	Hill	20 - 30	4	34	62	0.77/0.18	22
		113 - 123	-	-	-	-	18
	Abyssal	7 - 17	3	28	69	0.50/0.44	18
E	Plain	112 - 122	-	-	-	-	12
		207 - 217	3	36	61	1.99/0.94	1[illegible]
	Abyssal	5 - 15	-	-	-	-	1[illegible]
F	Plain (Sedi-	75 - 85	-	-	-	-	1[illegible]
	ments belong	120 - 130	-	-	-	-	18
	to abyssal	130 - 140	-	-	-	-	22
	hill province)	165 - 175	31	22	47	6.04/0.01	15
	Abyssal	0 - 15	-	-	-	-	18
FT	Plain	15 - 27	-	-	-	-	18
		27 - 37	5	24	71	3.86/0.14	2[illegible]
		37 - 48	-	-	-	-	2[illegible]
		48 - 58	-	-	-	-	14
		58 - 68	-	-	-	-	1[illegible]
	Abyssal	12 - 22	8	29	63	3.91/0.14	1[illegible]
G	Plain	66 - 76	-	-	-	-	1[illegible]
	(Top is	76 - 86	-	-	-	-	1[illegible]
	pelagic)	96 - 106	-	-	-	-	1[illegible]
		141 - 151	14	36	50	4.23/0.22	1[illegible]
	Abyssal	0 - 18	-	-	-	-	1[illegible]
GT	Plain						
	(Top is						
	pelagic)						

NOTE: It was not possible to present the geographic coordinates of the St

*c is considered to be approximately equal to the vane shear strength, S

Table 4. Results

(%)	Original Water Content, W	Specific Gravity, G_s	Void Ratio, e	Liquid Limit, LL	Plastic Limit, PL	Plasticity Index, PI (%)	Liquidity Index, LI	Wet Unit Weight, γ (gm/cm^3)	Effective Overburden Pressure, $\overline{p}$ (gm/cm^2)
	208	2.41	5.00	152	82	70	181	1.24	16.9
	224	-	5.41	167	69	98	160	1.22	40.9
	323	-	7.85	164	99	65	343	1.16	2.1
	285	2.43	6.92	205	105	100	181	1.18	18.3
	296	-	7.20	214	107	107	178	1.17	35.2
	167	2.55	4.25	109	59	50	218	1.30	4.8
	174	-	4.44	119	67	53	206	1.28	42.2
	231	-	5.73	127	75	52	301	1.22	1.1
	223	2.48	5.52	155	81	74	191	1.23	5.3
	186	-	4.62	131	86	45	225	1.26	27.6
	186	2.48	4.62	112	47	65	215	1.26	2.9
	126	-	3.21	90	50	40	191	1.37	39.6
	113	2.55	2.88	87	41	46	159	1.40	75.7
	170	-	4.33	104	58	46	242	1.29	2.7
	137	-	3.50	78	52	26	328	1.35	25.8
	186	-	4.77	114	68	46	257	1.27	37.0
	228	-	5.83	137	105	32	391	1.23	39.1
	152	2.57	3.91	104	55	49	200	1.32	49.6
	189	-	4.81	111	60	51	254	1.27	1.9
	180	-	4.60	100	66	34	340	1.28	5.3
	231	2.55	5.90	109	59	50	347	1.22	7.5
	213	-	5.42	101	69	32	461	1.24	9.9
	145	-	3.69	-	-	-	-	1.33	13.2
	100	-	2.58	63	49	14	371	1.44	17.4
	127	2.55	3.24	81	48	33	244	1.37	6.0
	133	-	3.41	99	48	51	167	1.35	23.8
	115	-	2.94	82	45	37	192	1.40	27.6
	134	-	3.44	-	-	-	-	1.35	34.2
	105	2.56	2.69	78	55	23	218	1.42	52.5
	143	-	3.65	86	54	32	281	1.33	2.8

of the Stations.

ength, S

uid- ex, LI	Wet Unit Weight, γ (gm/cm^3)	Effective Overburden Pressure, $\overline{p}$ (gm/cm^2)	Vane Shear Strength Original, c (gm/cm^2)*	Vane Shear Strength Remolded (gm/cm^2)	Vane Shear Strength Sensi-tivity	c/$\overline{p}$ Ratio
81	1.24	16.9	32.2	6.1	5.3	1.9
60	1.22	40.9	35.8	6.6	5.4	0.9
43	1.16	2.1	11.6	3.0	3.9	5.5
81	1.18	18.3	62.5	7.6	8.2	3.4
78	1.17	35.2	60.0	6.1	9.8	1.7
18	1.30	4.8	69.8	7.1	9.8	14.5
06	1.28	42.2	55.8	5.6	9.9	1.3
01	1.22	1.1	5.7	2.3	2.5	5.2
91	1.23	5.3	45.0	6.6	6.8	8.5
25	1.26	27.6	75.2	14.5	5.2	2.7
15	1.26	2.9	10.0	4.0	2.5	3.4
91	1.37	39.6	26.6	9.1	2.9	0.7
59	1.40	75.7	48.0	11.2	4.3	0.6
2	1.29	2.7	16.7	3.2	5.2	6.2
8	1.35	25.8	30.8	6.8	4.5	1.2
57	1.27	37.0	37.2	10.6	3.5	1.0
91	1.23	39.1	38.5	10.4	3.7	1.0
90	1.32	49.6	54.0	12.5	4.3	1.1
4	1.27	1.9	16.6	7.1	2.3	8.7
0	1.28	5.3	22.3	8.1	2.8	4.2
7	1.22	7.5	20.6	7.8	2.6	2.7
1	1.24	9.9	24.5	8.8	2.8	2.5
	1.33	13.2	32.3	9.4	3.4	2.4
1	1.44	17.4	31.2	10.4	3.0	1.8
4	1.37	6.0	35.3	9.9	3.6	5.9
7	1.35	23.8	62.4	12.5	5.0	2.6
2	1.40	27.6	104.0	27.0	3.8	3.8
	1.35	34.2	125.5	33.4	3.6	3.7
8	1.42	52.5	132.8	37.1	3.6	2.5
1	1.33	2.8	26.4	6.4	4.1	9.4

Continued

Station	General Sediment Environment	Sediment Depth (cm)	% Sand	% Silt	% Clay	Carbonate Carbon/ Organic Carbon Content (%)	Orig Wate Cont W
	Abyssal	0 - 13	-	-	-	-	101
H	Plain	64 - 77	-	-	-	-	71
		77 - 88	-	-	-	-	91
		98 - 108	34	22	44	2.14/0.14	68
		108 - 118	-	-	-	-	64
		148 - 158	-	-	-	-	90
	Continental	0 - 10	-	-	-	-	65
I-1	Terrace	20 - 33	-	-	-	-	64
		33 - 43	17	20	63	1.77/0.51	50
	Continental	0 - 12	61	10	29	2.86/2.73	73
I-4	Terrace	22 - 34	-	-	-	-	79
		45 - 58	46	14	40	2.68/1.73	79
	Continental	0 - 13	-	-	-	-	85
J	Terrace	23 - 36	73	9	18	9.23/0.60	82
		46 - 56	-	-	-	-	76
		66 - 76	71	12	17	8.96/0.48	68
		86 - 96	-	-	-	-	64
	Abyssal	0 - 12	5	18	77	3.12/0.86	255
K	Plain	22 - 32	-	-	-	-	197
		42 - 52	-	-	-	-	20
		62 - 72	9	18	73	4.33/1.10	183
		72 - 82	-	-	-	-	182
	Abyssal	87 - 97	11	19	70	-/1.05	361
		107 - 117	-	-	-	-	341
		157 - 167	-	-	-	-	303
L-1	Plain	177 - 187	-	-	-	-	294
		229 - 239	-	-	-	-	287
		249 - 259	-	-	-	-	271
LT-1	Abyssal	0 - 13	-	-	-	-	273
		23 - 33	-	-	-	-	265
		43 - 53	-	-	-	-	405
		53 - 63	-	-	-	-	394

Table 4. Continued.

ate / c t (%)	Original Water Content, W	Specific Gravity, G_s	Void Ratio, e	Liquid Limit LL	Plastic Limit, PL	Plas-ticity Index, PI (%)	Liquid-ity Index, LI	Wet Unit Weight, γ (gm/cm^3)	Effective Overburden Pressure, P (gm/cm^2)
	101	-	2.71	71	37	34	191	1.45	2.8
	77	-	2.07	62	37	25	161	1.55	36.7
	91	-	2.44	67	37	0	182	1.49	41.7
.14	68	2.68	1.81	51	30	5	205	1.60	53.6
	64	-	1.70	38	28	0	337	1.62	59.6
	90	-	2.41	71	44	27	173	1.49	78.4
	65	-	1.71	45	27	18	213	1.60	2.9
	64	-	1.65	60	33	27	116	1.60	15.4
.51	50	2.60	1.29	83	44	39	16	1.70	23.2
.73	73	2.62	1.92	51	-	-	-	1.55	3.2
	79	-	2.07	53	-	-	-	1.53	14.4
.73	79	2.62	2.08	-	-	-	-	1.53	26.4
	85	-	2.24	-	-	-	-	1.51	3.2
.60	82	2.65	2.17	-	-	-	-	1.52	14.7
	76	-	2.01	-	-	-	-	1.55	26.1
.48	68	2.65	1.80	-	-	-	-	1.71	39.9
	64	-	1.70	-	-	-	-	1.61	51.7
.86	255	2.50	6.37	116	63	53	365	1.20	1.1
	197	-	4.92	106	52	54	270	1.25	5.9
	205	-	5.14	111	57	54	276	1.25	10.5
.10	183	2.51	4.59	114	64	50	237	1.27	15.5
	182	-	4.57	116	65	51	232	1.27	18.0
	361	2.33	8.41	156	91	65	419	1.14	11.0
	341	-	7.94	160	87	73	350	1.15	13.6
	303	-	7.06	145	-	-	-	1.17	21.1
	294	-	6.85	144	71	73	307	1.17	24.1
	287	-	6.69	147	73	74	288	1.17	31.9
	271	-	6.31	188	100	88	196	1.18	35.1
	273	-	6.50	143	87	56	334	1.18	1.0
	265	-	6.30	125	107	18	890	1.19	4.7
	405	-	9.65	153	-	-	-	1.13	6.9
	394	-	9.38	163	-	-	-	1.13	8.0

iquid-ty ndex, LI	Wet Unit Weight, γ (gm/cm^3)	Effective Overburden Pressure, $\bar{p}$ (gm/cm^2)	Vane Shear Strength			$c/\bar{p}$ Ratio
			Original, c (gm/cm^2)	Remolded (gm/cm^2)	Sensi-tivity	
191	1.45	2.8	25.9	6.8	3.8	9.2
161	1.55	36.7	97.6	20.1	4.9	2.7
182	1.49	41.7	55.4	10.4	5.3	1.3
205	1.60	53.6	80.4	17.7	4.5	1.5
337	1.62	59.6	34.8	8.1	4.3	0.6
173	1.49	78.4	40.0	10.7	3.7	0.5
213	1.60	2.9	13.8	2.8	4.9	4.8
116	1.60	15.4	36.9	7.0	5.3	2.4
16	1.70	23.2	161.0	55.2	2.9	6.9
-	1.55	3.2	29.1	3.2	9.1	9.1
-	1.53	14.4	20.1	3.5	5.7	1.4
-	1.53	26.4	44.8	6.2	7.2	1.7
-	1.51	3.2	5.8	2.1	2.8	1.8
-	1.52	14.7	20.3	2.1	9.7	1.4
-	1.55	26.1	30.0	1.6	18.8	1.1
-	1.71	39.9	48.7	4.5	10.8	1.2
-	1.61	51.7	-	-	-	-
365	1.20	1.1	5.5	0		5.0
270	1.25	5.9	15.1	4.7	3.2	2.6
276	1.25	10.5	20.3	7.3	2.8	1.9
237	1.27	15.5	29.0	6.8	3.5	1.5
232	1.27	18.0	23.4	7.8	3.0	1.3
419	1.14	11.0	31.6	8.1	3.9	2.9
350	1.15	13.6	28.2	7.9	3.6	2.1
-	1.17	21.1	32.6	8.4	3.9	1.5
307	1.17	24.1	35.2	9.4	3.7	1.5
288	1.17	31.9	46.9	12.5	3.8	1.5
196	1.18	35.1	55.1	15.6	3.5	1.6
334	1.18	1.0	9.7	3.1	3.1	9.7
890	1.19	4.7	32.6	7.8	4.2	6.9
-	1.13	6.9	26.6	7.8	3.4	3.9
-	1.13	8.0	29.3	9.4	3.1	3.7

Continued

Station	General Sediment Environment	Sediment Depth (cm)	% Sand	% Silt	% Clay	Carbonate Carbon/ Organic Carbon Content (%)
	Abyssal	0 - 5	-	-	-	-
		5 - 18	-	-	-	-
		18 - 31	-	-	-	-
LT-2	Plain	31 - 44	11	21	68	-/0.44
		44 - 57	-	-	-	-
		57 - 70	-	-	-	-
	Abyssal	0 - 13	-	-	-	-
		23 - 33	-	-	-	-
M	Plain	33 - 43	-	-	-	-
		53 - 63	1	57	42	0.20/0.31
		63 - 73	-	-	-	-
		73 - 83	-	-	-	-
		96 - 106	-	-	-	-
	Abyssal	7 - 20	-	-	-	-
N	Hill	30 - 40	13	30	57	3.34/0.23
		40 - 50	-	-	-	-
		50 - 60	-	-	-	-
		60 - 70	-	-	-	-
		80 - 90	-	-	-	-
		120 - 130	7	22	71	5.02/0.16
		130 - 140	-	-	-	-
	Abyssal	0 - 10	-	-	-	-
O	Plain	20 - 30	20	19	61	8.13/-
		30 - 40	-	-	-	-
		50 - 60	-	-	-	-
		60 - 70	18	21	61	8.04/0.61
		70 - 80	-	-	-	-
	Abyssal	0 - 10	-	-	-	-
OT	Plain	20 - 30	-	-	-	-
		30 - 40	-	-	-	-
		40 - 50	-	-	-	-
	Abyssal	16 - 26	12	13	75	3.40/0.75
P	Plain	26 - 36	-	-	-	-
		46 - 56	-	-	-	-
		56 - 66	6	29	65	1.17/0.85

Table 4. Continued.

Carbonate Carbon/ Organic Carbon Content (%)	Original Water Content, W	Specific Gravity, G_s	Void Ratio, e	Liquid Limit, LL	Plastic Limit, PL	Plasticity Index, PI (%)	Liquidity Index, LI	Wet Unit Weight, γ (gm/cm^3)
-	316	-	7.52	145	90	55	410	1.16
-	246	-	5.85	135	85	50	323	1.20
-	220	-	5.24	123	76	47	309	1.22
-/0.44	322	2.38	7.66	131	99	32	702	1.16
-	375	-	8.75	145	79	66	452	1.14
-	366	-	8.53	164	-	-	-	1.14
-	84	-	2.24	-	-	-	-	1.52
-	54	-	1.45	35	29	6	421	1.68
-	67	-	1.78	42	32	10	356	1.67
0.20/0.31	77	2.67	2.06	47	28	19	261	1.55
-	57	-	1.52	39	26	13	232	1.66
-	52	-	1.38	39	26	13	204	1.70
-	90	-	2.40	74	53	21	181	1.49
-	138	-	3.60	74	42	32	302	1.35
3.34/0.23	126	2.53	3.18	93	40	53	164	1.37
-	144	-	3.65	60	44	16	635	1.33
-	117	-	2.95	66	51	15	430	1.39
-	96	-	2.42	56	44	12	437	1.45
-	131	-	3.31	95	49	46	178	1.35
5.02/0.16	122	2.62	3.19	83	46	37	204	1 39
-	113	-	2.97	80	43	36	191	1.41
-	127	-	3.33	66	46	20	409	1.37
8.13/-	128	2.61	3.33	68	50	18	436	1.37
-	146	-	3.81	73	59	14	655	1.33
-	121	-	3.31	76	41	35	226	1.40
8.04/0.61	122	-	3.33	84	48	36	203	1.40
-	119	2.73	3.24	80	49	31	227	1.41
-	120	-	3.14	67	46	21	354	1.39
-	139	-	3.64	68	53	15	574	1.35
-	142	-	3.70	77	45	32	311	1 34
-	121	-	3.18	62	49	13	535	1.39
3.40/0.75	134	2.57	3.45	99	48	51	170	1.35
-	125	-	3.21	95	48	47	164	1.37
-	126	-	3.37	86	45	41	200	1.38
1.17/0.85	111	2.67	2.97	77	40	37	193	1.42

quid- y dex, LI	Wet Unit Weight, γ (gm/cm3)	Effective Overburden Pressure, $\overline{p}$ (gm/cm^2)	Vane Shear Strength			$c/\overline{p}$ Ratio
			Original c (gm/cm^2)	Remolded (gm/cm^2)	Sensitivity	
410	1.16	0.4	10.4	0		26.0
323	1.20	2.0	21.6	6.0	3.6	10.8
309	1.22	4.6	39.1	11.6	3.4	8 5
702	1.16	6.4	33.0	8.4	3 9	5.2
452	1.14	8.0	33.8	8.6	3.9	4.2
-	1.14	9.6	40.5	9.4	4.3	4.2
-	1.52	3.2	6.1	0		1.9
421	1.68	18.0	13.5	3.2	4.2	0.8
356	1.67	24.5	20.0	3.4	5.9	0.8
261	1.55	35.1	23.7	6.0	4.0	0.7
232	1.66	41.5	33.6	7.1	4.7	0.8
204	1.70	48.3	35.7	8.4	4.2	0.7
181	1.49	59.1	166.8	42.8	3.9	2.8
302	1.35	4.5	30.0	7.5	4.0	6.7
164	1.37	12.0	69.4	13.0	5.3	5.8
635	1.33	15.1	65.2	13.0	5.0	4.3
430	1.39	18.8	79.6	15.6	5.1	4.2
437	1.45	23.1	42.7	10.7	4.0	1.8
178	1.35	29.7	79.6	17.1	4.7	2.7
204	1 39	44.5	76.6	16.3	4.7	1.7
191	1.41	48.4	71.8	16.1	4.5	1.5
409	1.37	1.8	17.3	3.2	5.4	9 6
436	1.37	8.8	24.2	5.8	4.2	2.8
655	1.33	11.9	25.0	5.2	4.8	2.1
226	1.40	19.5	63 2	12.0	5.3	3 2
203	1.40	23.3	57.3	11.7	4.9	2.5
227	1.41	27.2	64.6	13.5	4.8	2.4
354	1.39	1.8	28.9	4.2	6.9	16.1
574	1.35	8.4	34.9	6.0	5.8	4.2
311	1 34	11.6	36.0	7.3	4 9	3.1
535	1.39	15.3	30.8	5.5	5.6	2.0
170	1.35	6.9	74.2	13.0	5.7	10.8
164	1.37	10.4	83.2	18.7	4.4	8.0
200	1.38	17.6	46.2	11.0	4.2	2.6
193	1.42	21.6	44.3	7.9	4.5	2.1

Continued

Station	General Sediment Environment	Sediment Depth (cm)	% Sand	% Silt	% Clay	Carbonate Carbon/ Organic Carbon Content (%)	Ori Wat Con
PT	Abyssal Plain	5 - 12	-	-	-	-	1
Q	Abyssal Plain	0 - 10	-	-	-	-	1
		20 - 30	-	-	-	-	1
		40 - 50	5	19	76	0.69/0.87	1
QT	Abyssal Plain	9 - 18	-	-	-	-	1
R-1	Continental Terrace	10 - 20	61	12	27	4.46/0.74	
		50 - 60	-	-	-	-	
		90 - 100	24	24	52	0.73/2.10	
R-2	Continental Terrace	0 - 9	-	-	-	-	
		9 - 19	-	-	-	-	
		19 - 29	-	-	-	-	
		29 - 39	-	-	-	-	
		39 - 49	-	-	-	-	
		49 - 59	-	-	-	-	
		59 - 69	-	-	-	-	
		69 - 79	-	-	-	-	
R-3	Continental Terrace	0 - 10	84	5	11	4.90/0.98	
		10 - 20	-	-	-	-	
		20 - 30	-	-	-	-	
		30 - 40	-	-	-	-	
		40 - 50	-	-	-	-	
		50 - 60	83	5	12	4.54/0.53	
		60 - 68	-	-	-	-	
R-4	Continental Terrace	19 - 29	-	-	-	-	
		69 - 79	-	-	-	-	
		79 - 89	-	-	-	-	
		89 - 99	-	-	-	-	

Table 4. Continued.

Carbonate Carbon/ Organic Carbon Content (%)	Original Water Content, W	Specific Gravity, G_s	Void Ratio, e	Liquid Limit LL	Plastic Limit, PL	Plasticity Index, PI (%)	Liquidity Index, LI	Wet Unit Weight, γ (gm/cm^3)	Ef Ov Pr (g
-	156	-	4.00	109	47	62	177	1.31	
-	188	-	4.89	127	53	74	185	1.27	
-	175	-	4.55	148	53	95	130	1.29	
0.69/0.87	153	2.60	3.97	121	45	76	142	1.32	
-	136	-	3.53	107	50	57	153	1.35	
4.46/0.74	80	2.64	2.12	61	36	25	183	1.53	
-	55	-	1.45	-	-	-	-	1.67	
0.73/2.10	86	2.57	2.22	90	41	49	94	1.49	
-	59	-	1.57	-	-	-	-	1.65	
-	56	-	1.50	39	-	-	-	1.66	
-	55	-	1.48	40	-	-	-	1.67	1
-	51	-	1.36	-	-	-	-	1.70	2
-	47	-	1.24	-	-	-	-	1.74	2
-	43	-	1.13	-	-	-	-	1.78	3
-	60	-	1.35	34	-	-	-	1.71	4
-	55	-	1.46	41	-	-	-	1.67	5
4.90/0.98	68	2.66	1.82	-	-	-	-	1.59	
-	51	-	1.35	-	-	-	-	1.71	
-	50	-	1.34	-	-	-	-	1.71	1
-	46	-	1.24	-	-	-	-	1.75	2
-	46	-	1.23	-	-	-	-	1.75	3
4.54/0.53	40	2.67	1.06	-	-	-	-	1.81	3
-	42	-	1.11	-	-	-	-	1.79	4
-	48	-	1.27	-	-	-	-	1.74	1
-	39	-	1.06	-	-	-	-	1 81	5
-	47	-	1.20	36	-	-	-	1.71	6
-	67	-	1.71	58	-	-	-	1.58	6

Liquid-ity Index, LI	Wet Unit Weight, γ (gm/cm^3)	Effective Overburden Pressure, $\bar{p}$ (gm/cm^2)	Vane Shear Strength			$c/\bar{p}$ Ratio
			Original, c (gm/cm^2)	Remolded (gm/cm^2)	Sensi-tivity	
177	1.31	2.5	20.8	6.2	3.4	8.3
185	1.27	1.2	8.4	0		7.0
130	1.29	6.6	136.2	27.6	4.9	20.6
142	1.32	12.6	63.6	18.7	3.4	5.0
153	1.35	4.5	33.6	8.9	3.8	7.5
183	1.53	7.6	22.7	7.8	2.9	3.0
-	1.67	33.6	19.8	4.7	4.2	0.6
94	1.49	52.4	294.8	71.8	4.1	5.6
-	1.65	2.8	11.0	2.1	5.2	3.9
-	1.66	8.9	26.0	4.2	6.2	2.9
-	1.67	15.4	16.6	3.2	5.2	1.1
-	1.70	22.2	18.8	2.1	9.0	0.8
-	1.74	29.4	28.2	2.1	13.4	1.0
-	1.78	37.0	27.0	2.1	12.9	0 7
-	1.71	43.9	26.0	3.1	8.4	0.6
-	1.67	50.4	-	-	-	-
-	1.59	2.8	12.5	1.6	7.8	4.5
-	1.71	9.7	20.8	2.1	9.9	2.1
-	1.71	16.6	16.6	2.1	7.9	1.0
-	1.75	23.9	25.0	2.6	9.6	1.0
-	1.75	31.2	32.3	3.2	10.1	1.0
-	1.81	39.1	28.1	4.2	6.7	0.7
-	1.79	46.0	42.8	3.2	13.4	0.9
-	1.74	17.3	18.7	4.2	4.5	1.1
-	1 81	56.8	30.2	4.2	7.2	0.5
-	1.71	63.7	113.5	6.3	18.0	1.8
-	1.58	69.3	167.0	6.3	26.5	2.4

Continued

DISCUSSION OF RESULTS

The following sections review in a station-by-station sequence the results of the laboratory and vane shear test programs. Each section includes (1) a brief description of the geologic environment, (2) an identification of the sediment, and (3) an evaluation of the vane shear and laboratory test results.

Before the test results are discussed, several paragraphs are devoted to a critique of the sampling procedure. The critique considers the physical makeup of the sampling device, since these characteristics usually limit the quality of the sediment sample.

General

The gravity corer used to obtain the sediment sample has several deficiencies. The deficiencies affect the sampling operation by preventing the recovery of an undisturbed sample. Every corer disturbs the soil to a certain extent; however, the significance of disturbance changes as different disciplines are involved.

The civil engineer judges the quality of the soil sample on several parameters related to the corer's physical configuration. If the values of the limiting parameters are exceeded, the engineer considers the sample disturbed. The parameters used most frequently to define sample disturbance include the area ratio (Equation 1), the inside clearance ratio (Equation 9), and the outside clearance ratio (Equation 10).

$$C_I\ (\%) = 100\,\frac{LD - ID}{ID} \qquad (9)$$

where C_I = the inside clearance ratio

LD = linear diameter

ID = inner diameter of cutting head

$$C_O\ (\%) = 100\,\frac{OD - BD}{BD} \qquad (10)$$

where C_O = outside clearance ratio

OD = outer diameter of cutting head

BD = barrel diameter

According to Hvorslev (1965), the area ratio, inside clearance ratio, and outside clearance ratio should not exceed 20%, 0.5%, and 3%, respectively, if the sample is to be considered undisturbed. Hvorslev also recommends that the ratio of core length to core diameter be less than 20 and that a piston be employed during recovery.

Obviously, the corer utilized on the cruise exceeded some of the maximum values defined by Hvorslev (for example: A_r = 39 to 87%; C_I = 0%; and C_O = 8 to 17%). About half the cores also had length-to-diameter ratios larger than 20, and none of the corers utilized a piston.

It is generally believed that the soil adjacent to the wall of the corer is weakened most (Gray, 1957). Published data also show that the strength of the sample increases as the distance from the wall increases (Burmister, 1936). Unfortunately, the magnitude of strength decrease in the center portion of the sample varies from sample to sample. A greater loss usually occurs in soft soils than in stiff or strong soils. The top few centimeters of a core and the lower portion of a long (L/D greater than 20) core are expected to be disturbed to the greatest degree.

Since the surface area of vane rotation is less than 3.5% of the sample's cross-sectional area, the strength loss due to large area and clearance ratios should be small. The magnitude of loss was calculated to be approximately 10% by extrapolating the strength difference between the gravity corer at an area ratio of 39% and the trip corer at an area ratio of 50% back to strengths at an area ratio of 20%. No absolute magnitude is to be placed on the strength loss due to large length to core diameter ratios; however, the effect is believed to be significant for weak soils.

In the following paragraphs, a description of the sediments from each station is presented. The stations are designated by capital letters. The letter T in some designations indicates that the sample recovered by the trip corer was used in the analysis.

Station A

Geologic Considerations. Station A is located north of Palmyra, northern island in the Northwest Christmas Island Ridge (also called the Line Islands by Menard, 1964). The particular site, located in 2,850 fathoms of water, exhibited characteristics typical of an abyssal hill environment (Hamilton, 1970). Fine-grained pelagic materials dominate the sediments of the area (Fairbridge, 1966).

Sediment Identification. The gravity corer obtained 280 centimeters of homogeneous deep-sea red clay. A visual examination of the core (through the core liner) found no evidence of sample layering. The Unified Classification System, which describes a soil by its plasticity characteristics and grain size, designates the material as an inorganic silt of high compressibility (MH). The Trilinear Classification System considers the same material a silty clay. The median diameter of an increment from the core is 0.0024 millimeter. Clay size particles constituted approximately 66% of the sample. Silt particles accounted for 29% of the material, while sand formed the remainder. The carbonate carbon and organic carbon contents are 2.12% and 0.01%, respectively.

Vane Shear Strength and Index Properties. Vane shear strengths and index property data are plotted in Figure 3. Since only two sections were evaluated, no conclusive trends can be established. Although the data suggest that both the remolded and original strengths increase with depth, a greater increase would normally be expected. The high water content or possible sample disturbance (L/D $\approx$30) may account for the behavior.

Station B

Geologic Considerations. Station B is located between the Northwest Christmas Island Ridge and the Marshall and Gilbert Islands. The depth of water at the site exceeded 3,150 fathoms. A series of narrow throughs, which reach depths as great as 1,000 fathoms below the surrounding area, occur in the vicinity of the site (Fairbridge, 1966). Sediments at the site are typically composed of fine-grained pelagic materials.

Sediment Identification. The gravity corer obtained 235 centimeters of homogeneous deep-sea red clay. A visual examination of the core found no evidence of sample layering. The Unified Classification System designates the soil as an inorganic silt of high to very high compressibility (MH), while the Trilinear Classification System considers the material a silty clay. The median diameter of the particle distribution is less than 0.002 millimeter. The percentages of clay, silt, and sand size particles are 67, 22, and 11, respectively. Carbonate carbon and organic carbon contents are less than 0.18% of the sample.

Vane Shear Strength and Index Properties. Vane shear strengths and index properties are plotted in Figure 4. The index properties generally behave as expected (water content decreases with depth); however, the original strength determination on the deepest increment appears low. Since the length-to-diameter ratio exceeded 20, the increment may have been disturbed excessively during sampling. An increase in water content for constant plasticity index tends to substantiate this belief.

Station C

Geologic Considerations. Station C is located on the east side of the Kermadic-Tonga Trench. The trench to the west virtually isolates the site from sediments of terrigenous origin; therefore, sediment conditions are similar to the average deep Pacific situation, where the rate of deposition is slow and sediments are primarily pelagic in origin (Raitt et al., 1955). Depth of water at the site is approximately 3,100 fathoms.

Sediment Identification. The gravity corer obtained 209 centimeters of homogeneous deep-sea red clay. A visual examination of the core found

no evidence of sample layering. The soil is classified as an inorganic silt of moderately high compressibility (MH). The Trilinear System defines the material as a silty clay. The material has a median diameter equal to 0.0031 millimeter. The percentages of sand, silt, and clay size particles are 9, 30, 61, respectively. Carbonate carbon and organic carbon account for less than 2.0% of the sample.

Vane Shear Strength and Index Properties. Vane shear strengths and index properties are plotted in Figure 5. Since only two increments were evaluated, the trends established by the results are questionable. The decrease in original strength with depth probably suggests some form of sample disturbance. Although the L/D is 25, the strength loss probably arises from sample handling. The similarity in Atterberg limits indicates that no major mineralogic changes occurred.

Station D

Geologic Considerations. Station D is located in the central portion of the South Fiji Basin. Water depth at the site is 2,400 fathoms. Fairbridge (1966) finds that calcareous oozes made up of foraminiferal test dominate the sediments above 2,500 fathoms, while red clays usually occur below that depth. The high volcanic activity contributes minute particles of glass and shard to most surface sediments. Menard (1964) believes the abyssal plain of the basin is underlain by turbidities; however, recent ages find pelagic sedimentation dominating the depositional process.

Sediment Identification. The gravity corer obtained 137 centimeters of homogenous deep-sea red clay. No layering was found when the core was visually examined. The sediment is classified as an inorganic silt of high compressibility (MH) (Unified Classification System) and a silty clay (Trilinear System). The material has a median diameter of approximately 0.0026 millimeter. The percentages of sand, silt, and clay size particles are 4, 34, and 62, respectively. Carbonate carbon and organic carbon contents are less than 1.0%.

Vane Shear Strength and Index Properties. The strength and index properties are plotted in Figure 6. None of the plots exhibits unusual trends. The low original strength at the shallowest increment may reflect some sample disturbance; however, if the line between the first and second original strength readings were extended, the line would approximately pass through the origin (zero shear strength).

Station E

Geologic Considerations. Station E is located in the Tasman Sea, a marginal sea lying between Australia and New Zealand. The Sea correlates roughly with a deep basin known as the Tasman Basin. The site

has a water depth of approximately 2,650 fathoms. The slopes of the basin are furrowed with submarine canyons, which at one time channelled deposits to the deep-sea floor (Fairbridge, 1966; Standard, 1961). The present rate of accumulation from terrestrial sources is low; consequently, pelagic material overlies the turbidite deposits.

Sediment Identification. The gravity corer obtained 225 centimeters of material. The top 100 centimeters consisted of homogeneous deep-sea red clay, while the remaining portion of the core was composed of a gray-green silty clay. A visual examination of the core found no other distinctive layering. The red clay and gray-green silty clay were classified as inorganic silts of high compressibility (MH) (Unified Classification System) and silty clays (Trilinear System). The red clay and silty clay had median diameters of approximately 0.0015 and 0.0025 millimeter, respectively. The percentages of sand, silt, and clay size particles for the red clay sample were 3, 28, and 69, respectively. The gray-green clay was composed of 3% sand size particles, 36% silt size, and 61% clay size. Although the carbonate carbon and organic carbon compound contents of both samples were low (for example 1.0% and 3.0%), the gray-green silty clay did have the higher value of the two determinations.

Vane Shear Strength and Index Properties. The shear strength and index properties are plotted in Figure 7. No unusual trends occur. The length-to-diameter ratio of the core exceeds 35 for the lower increment, therefore, a high undisturbed in-situ strength might be expected.

Station F

Geologic Considerations. Station F is located on the western side of the New Hebrides Basin, one of three major basins in the Coral Sea. Pelagic red clays and globigerina oozes dominate surface materials of the basin (Fairbridge, 1966). Fine-grained silt-clays (including volcanic ash), deposited by once-active turbidity currents, lie beneath the surface sediments (Hamilton, 1970). Water depth at the site is approximately 2,400 fathoms.

Sediment Identification. The gravity corer obtained 220 centimeters of red clay and globigerina ooze. The sediment profile was composed of 50 centimeters of red clay above 80 centimeters of mottled red clay and globigerina ooze. The final 90 centimeters of sediment were globigerina ooze. The 60-centimeter trip corer verified the results from the gravity corer. The Unified Classification System defined the red clay as a clay of high plasticity (CH) and the globigerina ooze as an inorganic silt of high compressibility (MH). The Trilinear System designates the two samples as a silty clay and a sand-silt-clay, respectively. The red clay had a median diameter equal to 0.0019 millimeter, while the diameter for the ooze was 0.006 millimeter. The percentages of sand, silt, and

clay size particles for the red clay were 5, 24, and 71. The globigerina ooze was composed of 31% sand size particles, 22% silt size, and 47% clay size. Carbonate carbon and organic carbon accounted for approximately 4% of the red clay and 6% of the globigerina ooze.

Vane Shear Strength and Index Properties. The shear strength and index properties are plotted in Figures 8 and 9. Both the remolded and undisturbed vane strengths increase with depth. The trip corer strengths correlate quite well with the results of the gravity corer. The index property plots suggest that the water content of a globigerina ooze is greater than the water content of a red clay. The liquidity index of the ooze, however, tends to be less than the red clay. No conclusive statements can be made about the effect of the two materials on the Atterberg limits.

Station G

Geologic Considerations. Station G is located on the New Britain Basin, one of two major basins in the Solomon Sea. Turbidity currents at one time carried large quantities of terrigenous material to the basin's floor; however, the turbidity currents are no longer active. Consequently, pelagic sediments such as red clays and globigerina oozes dominate the surface material (Fairbridge, 1966). Bottom samples taken in adjacent areas by the Recorder Expedition (Krause, 1967) yielded 25 centimeters of buff ooze overlying 10 centimeters of blue volcanic clay. The site has a water depth of approximately 2,450 fathoms.

Sediment Identification. The gravity corer obtained 186 centimeters of sample. The soil profile included 50 centimeters of red clay above 70 centimeters of mottled red clay and gray-green silty clay. The remaining 66 centimeters of sample were composed of the gray-green silty clay. The Unified Classification System defined the red clay and the gray-green silty clay as inorganic silts of high compressibility (MH). The Trilinear System classified the red clay as a silty clay and the gray-green silty clay as a sand-silt-clay. The median diameters of the red and green clays were 0.0025 and 0.005 millimeter, respectively. The red clay was composed of 8% sand size particles, 29% silt size, and 63% clay size, while gray-green clay consisted of 14% sand size particles, 36% silt size, and 50% clay size. Carbonate carbon and organic carbon constituted less than 4.5% of both samples.

Vane Shear Strength and Index Properties. The strength and index properties are plotted in Figure 10. No unusual trends are detected in the strength plots. The gray-green clay has significantly higher strengths than the red clay. A strength determination on an 18-centimeter trip corer sample tends to verify the strength determination made on an upper interval of a gravity corer.

Station H

Geologic Considerations. Station H is located in the Coral Sea Basin, the largest of three basins in the Coral Sea. The water depth at the site is approximately 2,200 fathoms. An extremely flat abyssal plain characterizes geologic conditions at the site. Frause (1967) states that a thin layer of pelagic clay (12 to 40 centimeters) covers most of the basin. An olive-colored silt containing carbonized wood fragments lies beneath the clay. The silt is thought to be a turbidity deposit originating from subareal New Guinea (Fairbridge, 1966).

Sediment Identification. The gravity corer obtained 177 centimeters of tan silty clay. A visual examination found no evidence of layering. The Unified Classification System defined the sediment as an inorganic silt of high compressibility (MH), while the Trilinear System considered the sample a sand-silt-clay. The sediment had a median diameter equal to 0.0095 millimeter. The percentages of sand, silt, and clay size particles were 34, 22, and 44, respectively. Carbonate carbon and organic carbon accounted for approximately 2.5% of the sample.

Vane Shear Strength and Index Properties. The strength and index properties are plotted in Figure 11. A noticeable discontinuity occurs in the original strength profile. Since the remolded strength and soil plasticity do not exhibit a similar trend, the discontinuity is attributed to sample disturbance. The low L-versus-D ratio suggests that the disturbance occurred during handling.

Station I

Geologic Considerations. Station I is located in the Arafura Sea, north of the Gulf of Carpentaria and west of the Torres Straits. The site has a water depth of approximately 26 fathoms. Fairbridge (1966) states that terrigenous deposition is slow on the Arafura Shelf and that bottom sediments are generally glauconitic sand and calcareous mud. Recent geologic evidence tends to suggest that most of the Arafura Shelf was above sea level.

Sediment Identification. Two sediment cores were obtained from the station. The first sample, 58 centimeters long, was comprised of 20 centimeters of gray-green shelly, sandy clay above 12 centimeters of the aforementioned material mottled with a stiff dark silty clay. The remainder of the core was stiff dark silty clay. The other core was 83 centimeters in length, and it exhibited similar layering; however, the depth of the layers varied. The soils profile for this core consisted of 45 centimeters of gray-green shelly, sandy clay above 12 centimeters of mottled shelly, sandy clay and stiff dark silty clay. Beneath the mottled clay was the stiff dark silty clay. The median diameter of the gray-green material was 0.09 millimeter, while the corresponding value

for the dark silty clay was 0.0018 millimeter. The percentages of sand, silt, and clay size particles for the gray-green material were 61, 10, and 29, respectively. The stiff dark clay was composed of 17% sand size particles, 20% silt size, and 63% clay size. A grain size analysis was also performed on a sample from the apparently mottled zone. The results revealed an intermediate value for median diameter (0.03 millimeter) and intermediate percentage of fine-grained material (sand size = 46%; silt size - 14%; clay size = 40%). The Unified Classification System defined the gray-green material as a clayey sand (SC), the mottled material as inorganic silts and very fine sands with slight plasticity (ML), and the stiff dark clay as an inorganic silt of high compressibility (MH). The same materials were considered clayey sands, sandy clays, and sandy clays, respectively, by the Trilinear Classification System. Carbonate carbon and organic carbon varied between 2% and 6%.

Vane Shear Strength and Index Properties. The strength and index properties are plotted in Figures 12 and 13. Strength measurements in the upper portion of the core are suspected, since drainage undoubtedly occurred during sample testing. The lower increment, predominantly clay in size, probably represents the strength at that depth. The liquid limit of this increment exceeded the original water content of the sample. This behavior suggests that the sediment was above sea level at some time, and that desiccation may have occurred.

Station J

Geologic Description. Station J is located north of the Van Diemen Rise on the Sahul Shelf. The site has a water depth of 50 fathoms. A system of channels, terraces, and flat-topped banks characterize the bottom topography. The shelf is thought to have been above sea level during an early geologic period (Van Andel and Veevers, 1967). The sediments of the Timor Sea are generally thin. The coarser fractions are predominantly calcareous, while the fines are predominantly silts and clays of terrigenous origin. Deposits are continuously reworked by burrowing animals. Van Andel and Veevers (1967) found that the sediments near the site were dusky yellow-green shelly sands.

Sediment Identification. The gravity corer obtained 115 centimeters of sandy clay. The upper 40 centimeters of sample seemed to exhibit a greater concentration of shell debris. Both the Unified Classification System and Trilinear System considered the material a clayey sand (SC). The median diameter of the material was approximately 0.08 centimeter. Two core increments were tested for grain size. The percentage of sand, silt, and clay size particles in the first was 73, 9, and 18; while the second had values of 71, 12, and 17. Almost 10% of the material was carbonate carbon in origin. The values of organic carbon content were low (less than 1%).

Vane Shear Strength and Index Properties. The strength and index properties are plotted in Figure 14. Since cohesionless material constituted over 70% of the sample, drainage would occur during the shearing process. The drainage probably invalidates the strength data.

Station K

Geological Description. Station K is located west of the Timor Trough in the eastern portion of the Indian Ocean. The water depth at the site is 1,850 fathoms. The area is characterized by an abyssal plain. Terrigenous sediments originate from the Sahul Shelf, the Timor Trough, and the Sesser Sunda Islands. Since the source of terrigenous material has been reduced in recent decades, pelagic materials often occur in the top few centimeters of sample (Van Andel and Veevers, 1967). Below 1,000 fathoms, the pelagic material is often rich in radiolarians. Van Andel and Veever (1967) found sediments in the area to be primarily dusky yellow-green sands, silts, and clays with abundant skeletal debris.

Sediment Identification. The gravity corer obtained 90 centimeters of red clay and gray-green silty clay. A visual examination of the core found that the red clay occurred in the top 20 centimeters of sample. The next 30 centimeters of sample were defined as mottled red clay and gray-green silty clay. The remaining 40 centimeters were composed of a gray-green silty clay. The Unified Classification System defined the red clay and the gray-green silty clay as inorganic silts of high compressibility (MH). The Trilinear System classified both materials as silty clays. The median grain diameter of the red clay was 0.0015 millimeter, while the median diameter of the gray-green silty clay was 0.0013 millimeter. The percentages of sand, silt, and clay size particles in the red clay were 5, 18, and 77, respectively. The gray-green clay was, in turn, composed of 9% sand size particles, 18% silt size, and 73% clay size. Carbonate carbon and organic carbon constituted less than 6% of each sample.

Vane Shear Strength and Index Properties. The vane strengths and index properties are plotted in Figure 15. No unusual trends can be detected. Both materials exhibit a similar amount of plasticity; however, the liquidity index is considerably higher for the red clay.

Station L

Geologic Considerations. Station L is located south of the Java Trench in the North Australian Basin. The water depth at the site is 3,100 fathoms. The site, which lies between the Christmas and Exmouth Rises, has characteristics typical of many deep-sea plains (Hamilton, 1969). Although sediments in these basins are predominantly terrigenous in origin, a thin layer of pelagic material often occurs at the sediment

surface (Fairbridge, 1966). Soil profiles of cores taken during the MONSOON and LUSIAD expeditions (Scripps Institute of Oceanography, 1964) grade from dark brown "muds" at the surface to gray or green "muds" near the core bottom.

Sediment Identification. Two gravity cores and two trip cores were obtained from Station L. The second gravity core, which had an extremely high area ratio (87%), was used to verify the sediment profile at the site. The first gravity core from Station L was 283 centimeters long. The top 87 centimeters were lost during the disassembly of the coring apparatus. The sediment log below that depth consisted of 40 centimeters of red clay above 156 centimeters of greenish-gray silty clay. The 90-centimeter core obtained with the trip corer seemed to coincide with the top of the "intact" gravity core. Red clay was found in the upper 50 centimeters of trip core. The 40-centimeter interval below that depth was composed of mottled red clay and gray-green silty clay. The second trip corer exhibited the same layering as the initial trip corer. The Unified Classification System designated the samples as inorganic silts of high compressibility (MH). The Trilinear System defines both materials as silty clays. The median diameter of the red clay was 0.0019 millimeter, while the median diameter of the gray-green silty clay was 0.0016 millimeter. The red clay was composed of 11% sand size particles, 21% silt size, and 68% clay size. The percentages of sand, silt, and clay size particles for the other sediment were 11, 19, and 70, respectively. Carbonate carbon and organic carbon accounted for less than 0.5% of the red clay and less than 1.5% of the gray-green silty clay.

Vane Shear Strength and Index Properties. The vane strength and index properties are plotted in Figures 16 and 17. The plots show several interesting trends. In Figure 16, the original and undisturbed strengths increase rather consistently with depth. No large discontinuity occurs when the results on the trip core are substituted for the top portion of the gravity core. The strength readings from the second trip core (Figure 17) correspond closely with the strength measurements made on the first trip core. The second trip core also verfies the large increase in original water content appearing at the 50-centimeter depth. The large increase in water content seems to reflect some unique feature of the mottled material.

Station M

Geologic Considerations. Station M is located on the south flank of the Java Trench in the India-Australian Basin. The water depth at the site is approximately 3,600 fathoms. Although the Java Trench system collects most of the terrigenous sediments originating from the north and northeast, abyssal plains still characterize the geology at the site (Hamilton, 1970). Since much of western Australia is presently

arid, pelagic sedimentation now dominates the depositional processes. Fairbridge (1966) states that the red clays often merge locally with radiolarian oozes. Cores taken during the MONSOON Expedition (Scripps Institute of Oceanography, 1964) suggest that surface samples are fine-grained and green to blue in color.

Sediment Identification. The gravity corer obtained 130 centimeters of homogeneous gray silty clay. Approximately 5 centimeters of rustic-colored gray clay were detected at the top of the core. Visual examination found no other distinctive layers. The Unified Classification System defined the soil as an inorganic silt of medium compressibility (MH). The Trilinear System classified the material as a clayey silt. The material had a median diameter of 0.007 millimeter. The percentages of sand, silt, and clay size particles were 1, 57, and 42, respectively. Carbonate carbon and organic carbon constituted less than 0.5% of the sample.

Vane Shear Strength and Index Properties. The vane strengths and index properties are plotted in Figure 18. Strengths increase consistently with depth in the upper 75 centimeters. Beyond that depth a substantial strength increase occurs. Two theories might account for the significant increase. Either a change in sediment properties occurred or the sample densified during the coring process. The validity of vane shear tests on this sample might also be questioned. Since the material is predominantly silt sized, drainage during shear would be expected. The index properties also behave somewhat erratically.

Station N

Geologic Considerations. Station N is located west of the northern end of Sumatra. The site has a water depth of approximately 2,400 fathoms. The northern extension of the Java Trench separates the site from most of the effects of terrestrial runoff (Ewing, 1969). In a similar manner, the Nintyeast Ridge isolates the area from turbidites originating on the Ganges Cone. Fairbridge (1966) suggests that the sediments of the area are often characterized by globigerina oozes.

Sediment Identification. The gravity corer obtained 150 centimeters of tan silty clay. The sample appeared homogeneous throughout its length. The Unified Classification System considered the material an inorganic silt of high compressibility (MH). The Trilinear System defined the same soil as a silty clay. The soil had median grain diameters of 0.003 millimeter (30 to 40 centimeters) and 0.0015 millimeter (120 to 130 centimeters). The percentages of sand, silt, and clay size particles in the upper layer (30 to 40 centimeters) were 13, 30, and 57, respectively. A similar determination performed on the 120 to 130-centimeter increment found 7% sand size particles, 22% silt size, and 71% clay size. Carbonate carbon and organic carbon accounted for less than 3.5% of the upper increment and less than 5.5% of the lower increment.

Vane Shear Strength and Index Properties. The vane strengths and index properties are plotted in Figure 19. The original strength profile varies considerably throughout its length. This rather erratic tendency seems to correlate with a zone of substantially lower liquid limits. Although the water contents in the zone decrease (as the plastic indices remains relatively constant), a loss in original strength is recorded at the 60- to 70-centimeter increment. This behavior suggests disturbance to the sample. The lowest two sample intervals exhibit similar characteristics. The plasticity indices are relatively consistent, while the water contents decrease. Unfortunately, the strength also decreases. The most obvious explanation is again sample disturbance. However, this unique behavior might also be attributed to the mineralogic composition of the material. The author tends to favor the former explanation.

Station O

Geologic Considerations. Station O is located on the distal portion of the Ganges Cone in the Indian Ocean. The site, approximately 250 miles southeast of Ceylon, has a water depth of 2,350 fathoms. Sediments are usually terrigenous in origin (Fairbridge, 1966). An extrapolation of data presented by Siddquie (1967) suggests that many sediments are silts and clays. The percentages of carbonate compound are usually less than 25 percent. Similar sediments on the continental slopes are generally plastic and soft in consistency (Fairbridge, 1966). These Continental slope sediments are composed of clay minerals and microorganisms such as foraminifera and radiolaria.

Sediment Identification. A 90-centimeter gravity core and a 70-centimeter trip core were obtained from Station O. The upper 50 centimeters of both samples was composed of a tan silty clay. The sediment became grayer below that depth. Both materials were classified (Unified Classification System) as inorganic silts of high compressibility (MH). The Trilinear System categorized the materials as silty clays. The tan silty clay had a median diameter equal to 0.0022 millimeter, while the gray silty clay's median diameter was 0.0028 millimeter. The percentages of sand, silt, and clay size particles in the tan soil were 20, 19, and 61, respectively. The gray soil, in turn, was composed of 18% sand size particles, 21% silt size, and 61% clay size. Carbonate carbon and organic carbon constituted approximately 8.5% of each sample.

Vane Shear Strength and Index Properties. The vane strengths and index properties are plotted in Figures 20 and 21. The gravity core strengths generally increase with depth as expected. A large increase in strength occurs in a zone where plasticity indices are changing considerably. The trip core exhibits strengths that are usually higher than the measurements made on gravity core samples. However, the index properties of the two samples correlate quite well. The bottom portion of the trip core is thought to be disturbed.

Station P

Geologic Considerations. Station P is located in the Bay of Bengal, northeast of Ceylon. Most of the sediments in the area have been carried from the continental shelfs by turbidity currents (Ewing et al, 1969). A distribution chart by Siddquie (1967) shows that the sediments in the area are silty clays. Less than 5% of the material has grain sizes in excess of 0.1 millimeter. Calcium carbonate accounts for 5% to 10% of the sediments. The depth at the particular site is approximately 1,800 fathoms.

Sediment Identification. A 90-centimeter gravity core and a 25-centimeter trip core were obtained at Station P. The upper 31 centimeters of sample were composed of a brown clay. The brown clay was underlain by gray-green clay. The Unified Classification System defined the brown and gray-green clays as inorganic silts of high compressibility (MH). The Trilinear System classified both materials as silty clays. The median diameters of the two materials were approximately .001 millimeter for the brown clay and 0.0022 millimeter for the gray-green clay. The brown clay consisted of 12% sand size particles, 13% silt size, and 75% clay size. The percentages of sand, silt, and clay size particles for the gray-green material were 6, 29, and 65, respectively. Carbonate carbon and organic carbon accounted for 4% of the brown clay and 2% of the gray-green clay.

Vane Shear Strength and Index Properties. The vane strengths and index properties are plotted in Figure 22. A severe discontinuity occurs in the original strength profile. The discontinuity roughly corresponds to the transition from the brown clay to gray-green clay. A decrease in plasticity index and an increase in water content are also noted for this zone. Liquidity index also increases substantially for this zone. Although sample disturbance may have occurred, it is not thought to be the cause of the discontinuity.

Station Q

Geologic Considerations. Station Q is located in the central portion of the Andaman Basin. The water depth at the site is approximately 1,650 fathoms. Sediments at the site are predominantly terrigenous in origin. The Irrawaddy and Salwean Rivers deposit enormous amounts of sediment into the area. A system of channels and canyons assists in diverting these flows to the central basin (Fairbridge, 1966). The central basin is presently accumulating fine olive-green clays and deltaic sediments (Redolpho, 1964). Volcanic ash and foraminiferal oozes occur in some areas.

Sediment Identification. A 70-centimeter gravity core and a 20-centimeter trip core were obtained from the site. A thin, 3-centimeter

increment of red clay occurred at the top of both cores. The sediment log below that depth included approximately 10 centimeters of tan clay above a gray clay. The material was classified by the Unified Classification System as an inorganic silt of high compressibility (MH). The Trilinear System defined the material as a silty clay. The material had a median diameter equal to 0.001 millimeter. The percentages of sand, silt, and clay size particles were 5, 19, and 76. Carbonate carbon and organic carbon accounted for approximately 1.5% of the material.

Vane Shear Strength and Index Properties. The vane strength and index properties are plotted in Figure 23. The strength profiles increase drastically in the first 25 centimeters. Since a discontinuity of similar magnitude did not occur in the index properties, some unusual soil characteristic seems to exist at this level. Soil disturbance would not normally increase the strength of a cohesive material, particularly to the magnitude recorded. If the measurements are neglected, the strength profile (with the trip core data) behaves as might be expected. The increment in question may derive its strength from cementation; however, the carbonate carbon and organic carbon content determinations are low.

Station R

Geologic Considerations. Station R is located in the northern portion of the Malacca Straits. Depth at the site is 50 fathoms. Bottom conditions at the site are closely related to strong currents, debouching rivers, climatic variations, and the proximity of bordering land masses (Keller and Richards, 1967). Sediments consist of muddy sands and minor amounts of calcium carbonate (shells and foraminiferal tests). Kaolinite constitutes the dominant clay minerals; lesser amounts of illite and montmorillonite are also found. Much of the area was, at one time, above sea level (Fairbridge, 1966).

Sediment Identification. Four gravity cores were obtained from Station R. The general core log revealed a fine gray shelly sand (0 to 16 centimeters) and a stiff gray clay (75 to 120 centimeters). The percentages of sand, silt, and clay size particles for the three samples are listed in Table 5. The median diameters and carbon contents of the samples are also included.

Table 5. Properties at Station R

Soil Type	Particle Size (%)			Median Diameter (mm)	Carbonate Carbon Organic Carbon (%) Compound
	Sand	Silt	Clay		
Shelly Sand	84	5	11	0.2	6.0
Sand	83	5	12	0.17	5.0
Clay	24	24	52	0.004	3.0

The Unified Classification System and Trilinear System defined the first two materials as sands with plastic fines (SC) and sands, respectively. The clay material was classified (Unified Classification System) as an inorganic silt with high compressibility and as a sand-silt-clay (Trilinear System).

Vane Shear Strength and Index Properties. The vane shear strengths and index properties are plotted in Figures 24 through 27. Any strength determination in the upper 75 centimeters of material is probably invalid, since the material was cohesionless (drainage could not be controlled, and coring or vane insertion changes soil density). The high values of strength recorded in the clay probably reflect sediment erosion or desiccation during past decades.

CORRELATION OF RESULTS

The sediments tested during this investigation represent materials from the following three physiographic provinces: (1) continental terraces, (2) abyssal plains, and (3) abyssal hills. Continental terrace provinces include all locations on the continental shelf and slope. Sediments, therefore, are primarily terrigenous in origin. The abyssal plain and abyssal hill provinces occur in the deep ocean (beyond the continental terrace). Terrigenous sediments originating from turbidity currents dominate the former province, while pelagic materials (red clays and oozes for example) characterize the latter. In some cases a pelagic material occurs in an abyssal plain province if the source of terrigenous material has been exhausted. However, the province is still considered an abyssal plain, since the underlying terrigenous deposits determine geomorphic characteristics of the area.

Unfortunately, the continental terrace samples tested contained a high percentage of sands. The high percentage of sand, in turn, invalidated the results of the vane shear tests (see STRENGTH CONSIDERATION - Vane Shear Strength and DISSCUSSION OF RESULTS - Stations I, J, and R for further explanation). Consequently, no correlations between strength and laboratory properties were attempted for the continental terrace sediment regime.

Sediment samples from the abyssal hill and abyssal plain provinces met most of the criteria required for vane shear testing. Although disturbance was suggested in several instances, the samples as a whole were thought to provide a good indication of the sediment strength. On the basis of this belief, it seemed appropriate to relate the results at one site to the results at another.

Since two sources of deposition are involved (continental runoff and biogenic activity), results are compared on a provincial basis. Pelagic sedimentation seems to occur at a more constant rate than the episodic deposition by turbidity currents; therefore, a better correlation was expected between sediments originating from abyssal hill provinces.

The first correlation, Figure 28, involves a plot of sediment strength versus increment depth. The plot shows a large scatter of "strength per depth" for the abyssal plain sediments. The episodic deposition of material seems to create a variety of strength values. The deviations suggest that either the mineralogic composition varies significantly during these events, or the particle arrangement differs with different events. Although the scatter of data for pelagic material is less, the results do not indicate a unique strength-versus-depth profile for pelagic materials. Both sediment types appear to have a finite value of strength at the soil-water interface. This value of strength generally varies from 5 to 25 gm/cm^2 at the soil-water interface to approximately 37 gm/cm^2 at a depth of 200 centimeters.

The $c/\bar{p}$ ratios were compared to the plasticity indices in Figures 29 and 30. The $c/\bar{p}$ ratio theoretically removes the effects of overburden pressure on the strength measurement. Once strength has been converted to this form, it can be compared to various index properties that depend upon the mineralogic characteristics of the material. Neither plot shows any noticeable correlation between the normalized strength and index properties. The scatter appears larger of the abyssal hill provinces. The plots do indicate that the plasticity indices and the $c/\bar{p}$ ratios are generally smaller for abyssal plain material. The $c/\bar{p}$ ratio exceeds four more than half the time for abyssal hill materials, while the similar ratio was usually less than four for abyssal plain materials. The minimum values of $c/\bar{p}$ for the abyssal plain and abyssal hill data are 0.5 and 0.9, respectively.

Similar plots, Figures 31 and 32, were used to compare the liquid limit to the $c/\bar{p}$ ratio for abyssal hill and abyssal plain provinces. Once again, the data from each plot were scattered. Since $c/\bar{p}$ varied with depth, a third set of plots evaluated the behavior at given depth increments ($c/\bar{p}$ versus liquid limit at 100-centimeter depth). Although the scatter of points decreased, no usable correlation appeared, and, therefore, the plots were not included.

These series of correlations seem to define a unique property of seafloor soils. In the upper 150 to 250 centimeters, the soil does not have a constant value of $c/\bar{p}$. The ratio decreases from infinity at the surface to approximately 0.4 at the aforementioned depths. The values of $c/\bar{p}$ vary widely in that depth range. The largest scatter occurs in sediments of pelagic origin. It is, therefore, assumed that the magnitude of intrinsic forces developed for surface sediments also varies significantly. Since the indices are unable to distinguish any difference, the function must depend on some time-dependent mechanism.

Figures 33 and 34 compare the liquidity index to the sensitivity. Although it was thought that the sensitivity would increase as the liquidity index increased, no significant correlation appears. However, it is interesting to note that the scatter of sensitivities for abyssal hill sediments exceeds the scatter of sensitivities for abyssal plain sediments. The average sensitivity of both materials is about 4.0, Terzaghi and Peck (1968) define clays with sensitivities of about 4.0 as "insensitive to sensitive".

Figure 35 compares the total carbon content with the original strength of the soil. The total carbon content include both the carbonate carbon and organic carbon contents. If the soil derived a significant portion of its strength form the carbon content, a relationship between shear strength and carbon content would be expected. However, these data fail to indicate such a relationship. It seems that for these soils carbon content plays an insignificant role in the development of strength.

SUMMARY AND CONCLUSIONS

Strengths and index properties were determined from soil samples taken at 18 locations in the southwest Pacific and eastern Indian Oceans. These data can be used to provide a preliminary indication of the seafloor soil conditions that exist in those ocean areas.

It is believed that the data presented for abyssal hill and abyssal plain provinces are sufficiently reliable to provide relative comparisons of soil conditions at different sites. Discrepancies between the test data and in-situ conditions that may be attributable to inadequate coring procedures, poor sample handling, or improper testing have been discussed. Since these discrepancies would typically lead to indications of soil strengths lower than those existing in situ, a foundation design based upon calculations using these data would be on the conservative side. However, the utilization of these data should be restricted to nonessential or expendable facilities.

With the test sites divided into three physiographic provinces, namely continental terrace, abyssal plain, and abyssal hill, a significant amount of data scatter was found to exist between similar provinces. Before it will be possible to develop regional charts of soil properties, more precise definitions of the boundaries of physiographic provinces will be required.

The shear strength and index properties of abyssal hill and abyssal plain sediments differ. The nature of the difference may depend upon the mineral constituents of the material; the dependency appears to be masked by time-dependent phenomena. Sediment strengths in the upper 150 to 300 centimeters showed little relationship to index properties. Consequently, a disturbed sample cannot presently serve as an index of the sediment strength.

RECOMMENDATIONS

The results of the investigation suggest several areas for additional research:

1. Correlate the effect of high area ratio of corers on strength loss. In particular, determine the strength loss at the center of a gravity core.

2. Investigate the mechanism of soil strength in the upper 150 to 300 centimeters of soil.

3. Determine the effect of carbonate carbon and organic carbon content on sediment strength.

4. Establish the areal variability of abyssal plain and abyssal hill soils in order to determine if limited coring can adequately represent a particular seafloor province.

5. Continue assembling engineering properties of various geographic provinces.

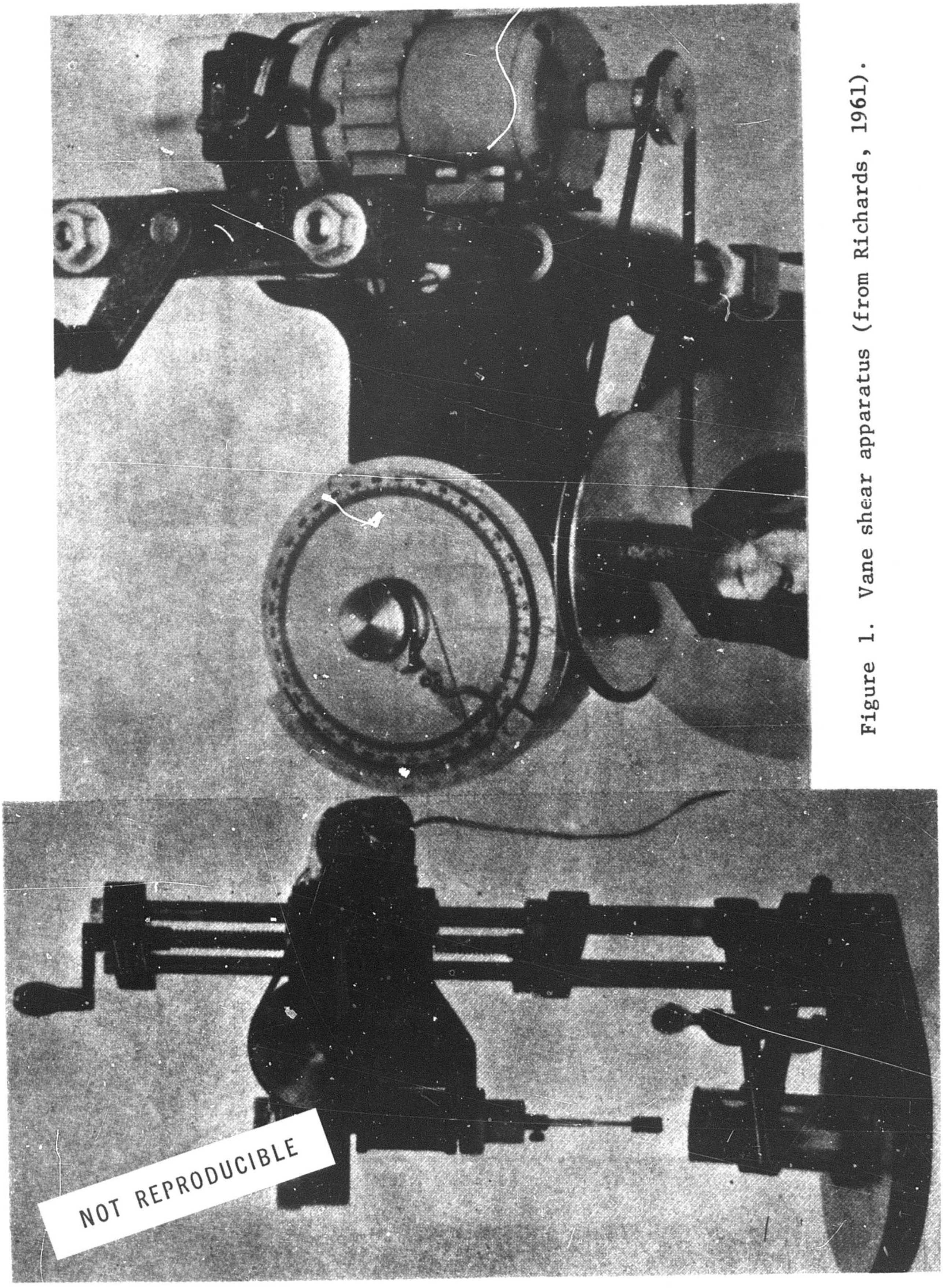

Figure 1. Vane shear apparatus (from Richards, 1961).

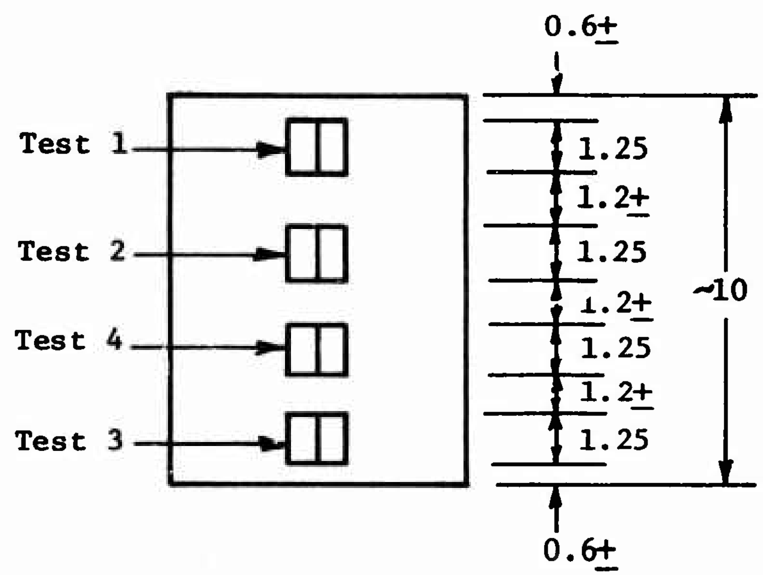

Figure 2. Spacing of vane shear tests (all dimensions in centimeters).

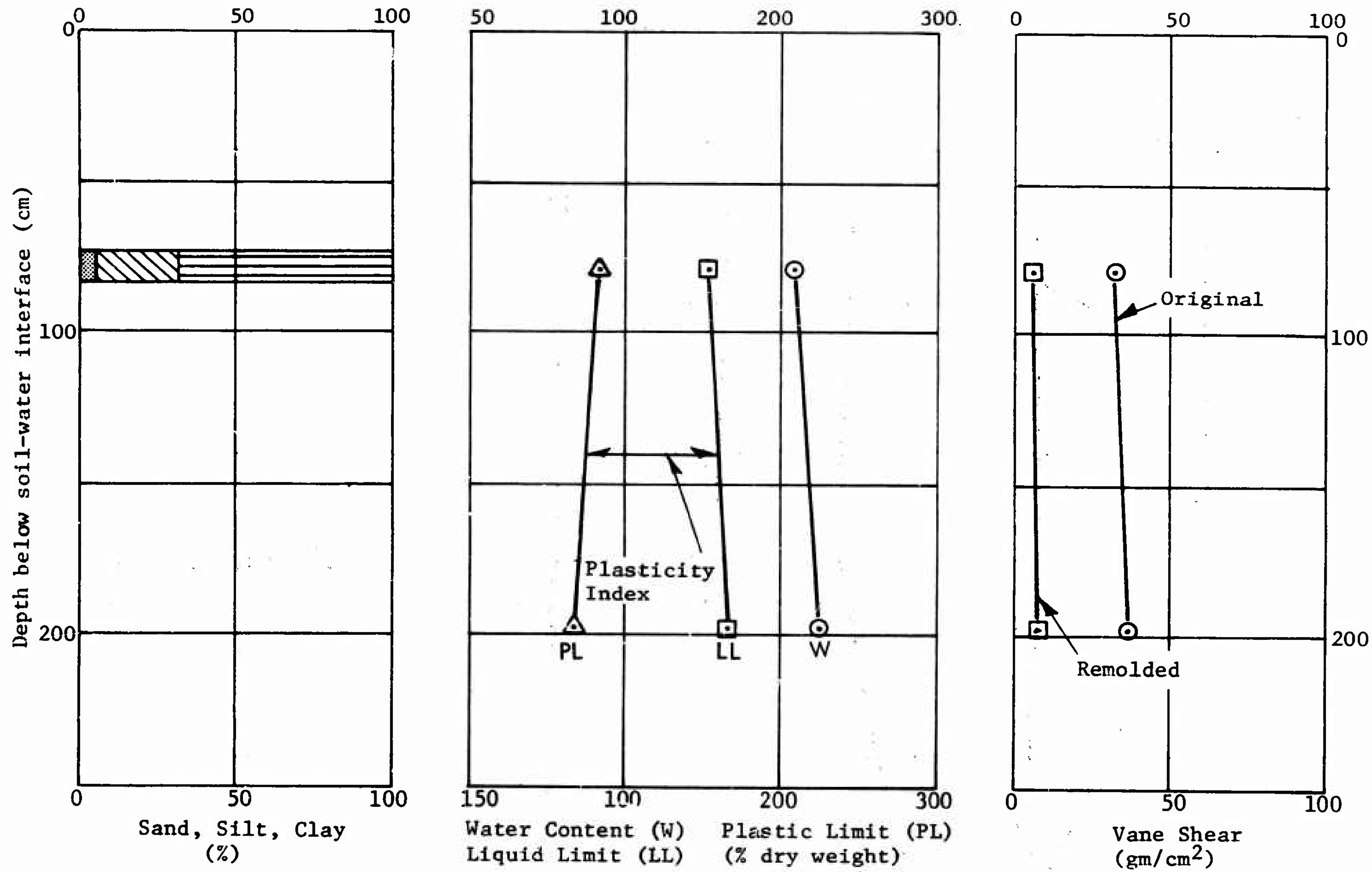

Figure 3. Soil parameters versus depth for Station A.

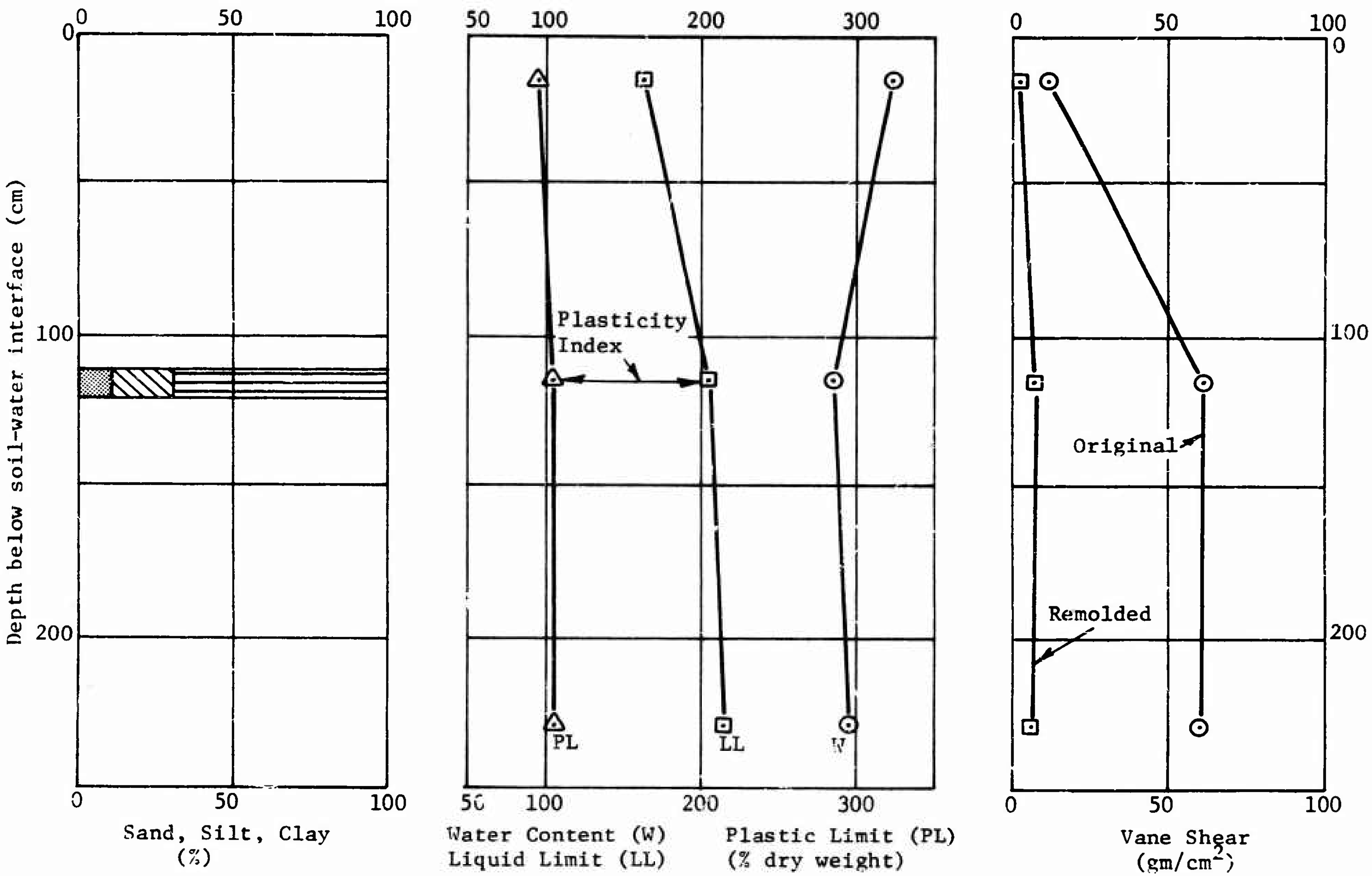

Figure 4. Soil parameters versus depth for Station B.

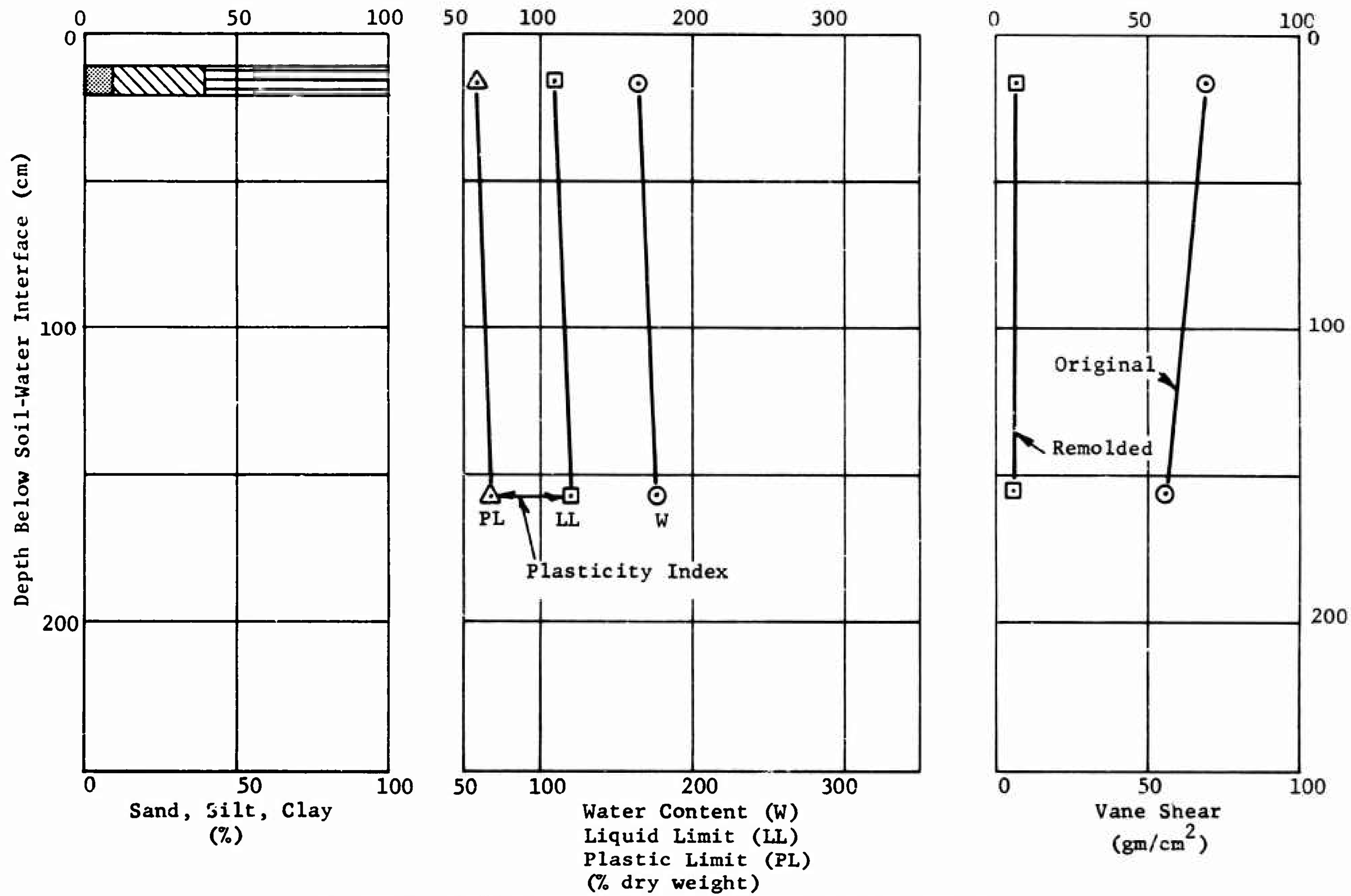

Figure 5. Soil parameters versus depth for Station C.

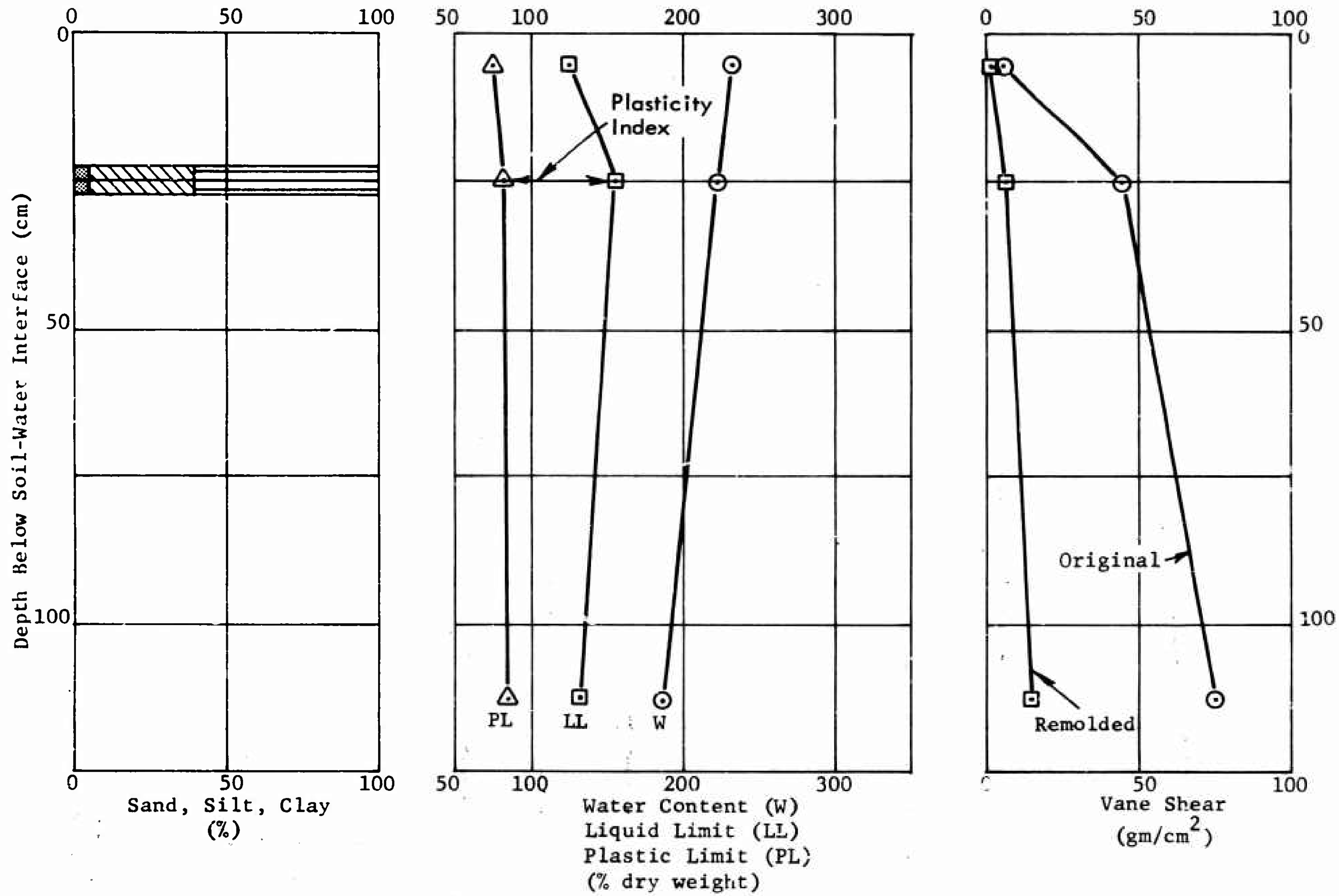

Figure 6. Soil parameters versus depth for Station D.

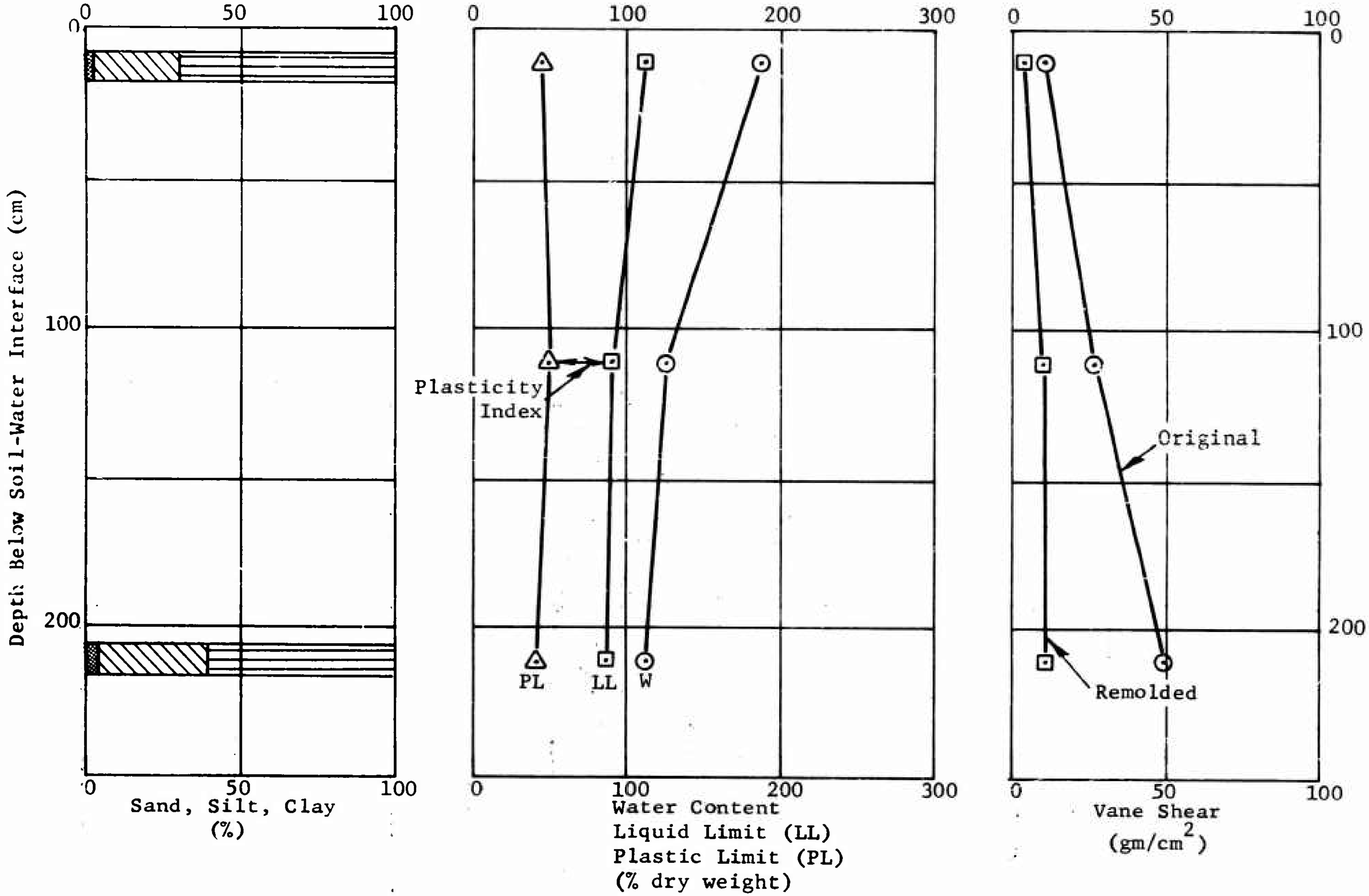

Figure 7. Soil parameters versus depth for Station E.

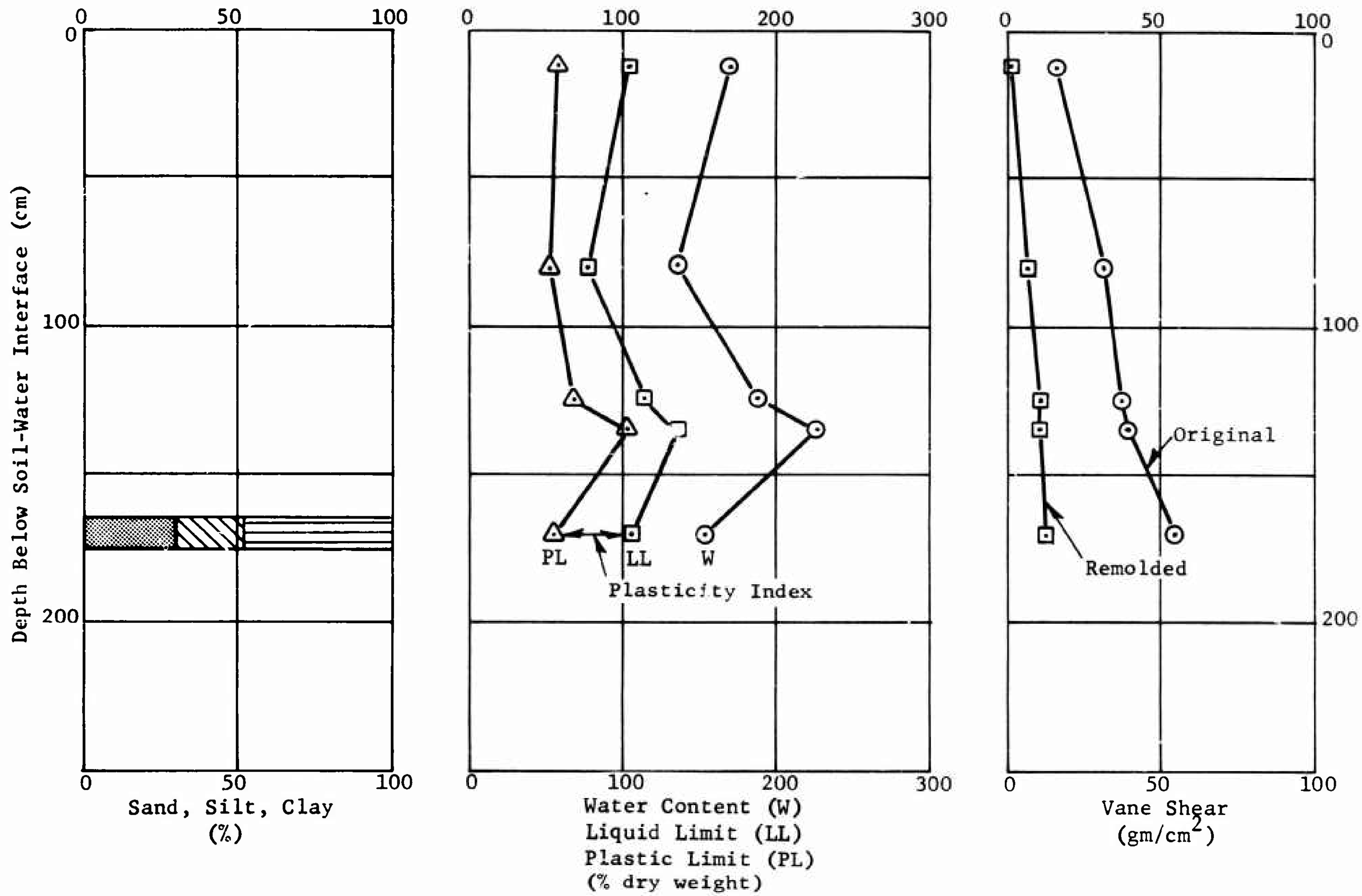

Figure 8. Soil parameters versus depth for Station F.

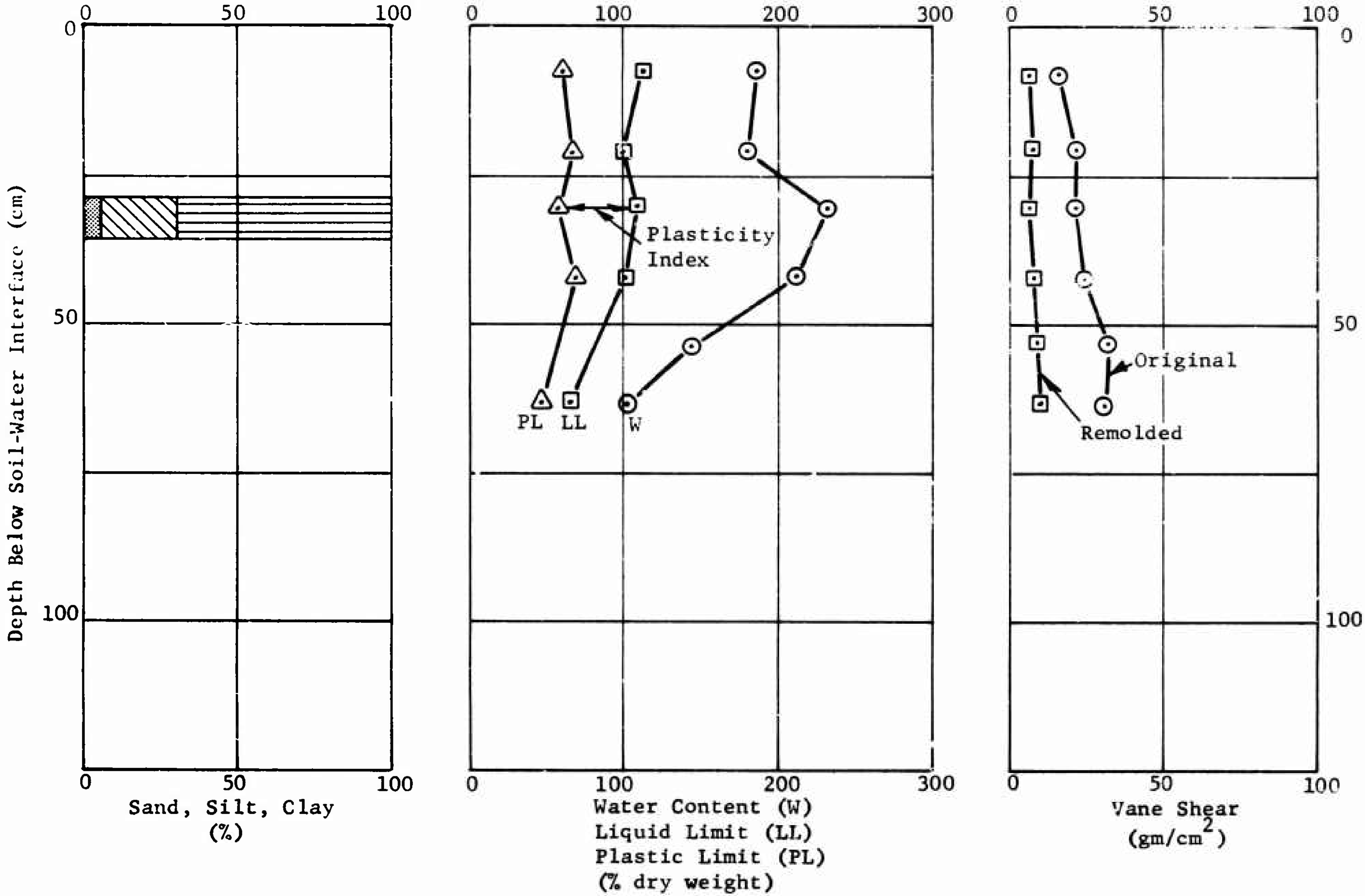

Figure 9. Soil parameters versus depth for Station FT.

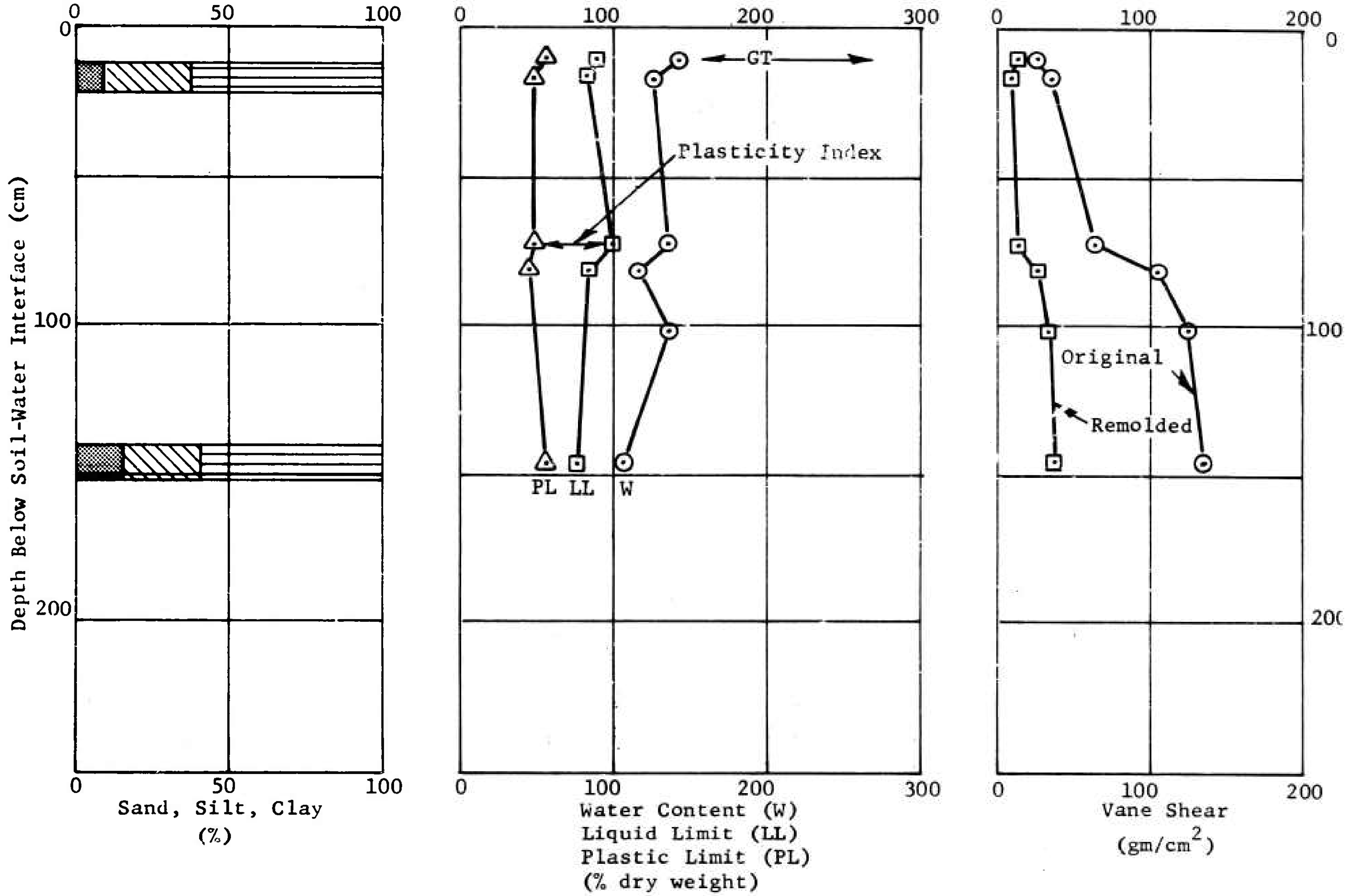

Figure 10. Soil parameters versus depth for Station G.

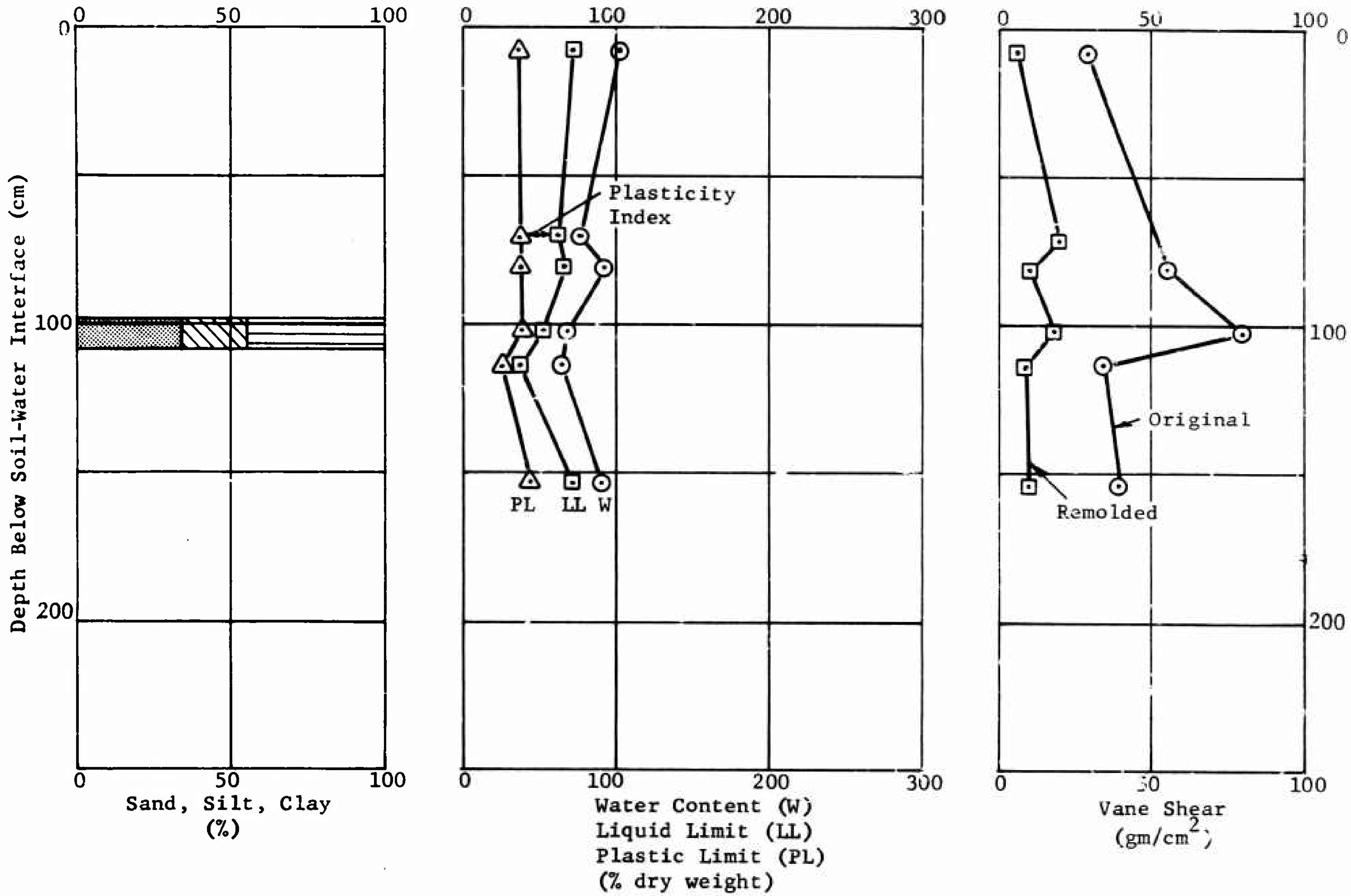

Figure 11. Soil parameters versus depth for Station H.

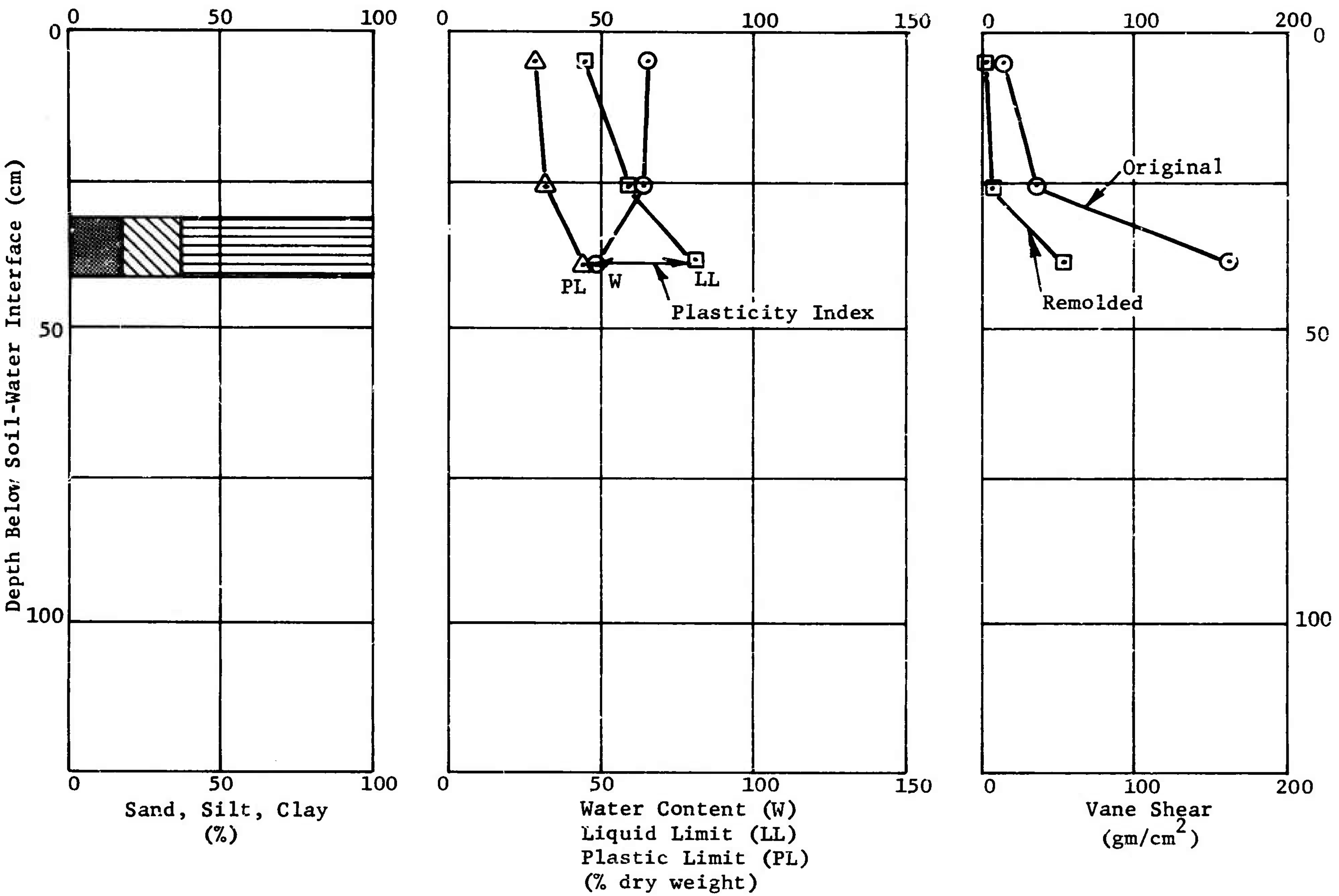

Figure 12. Soil parameters versus depth for Station I1.

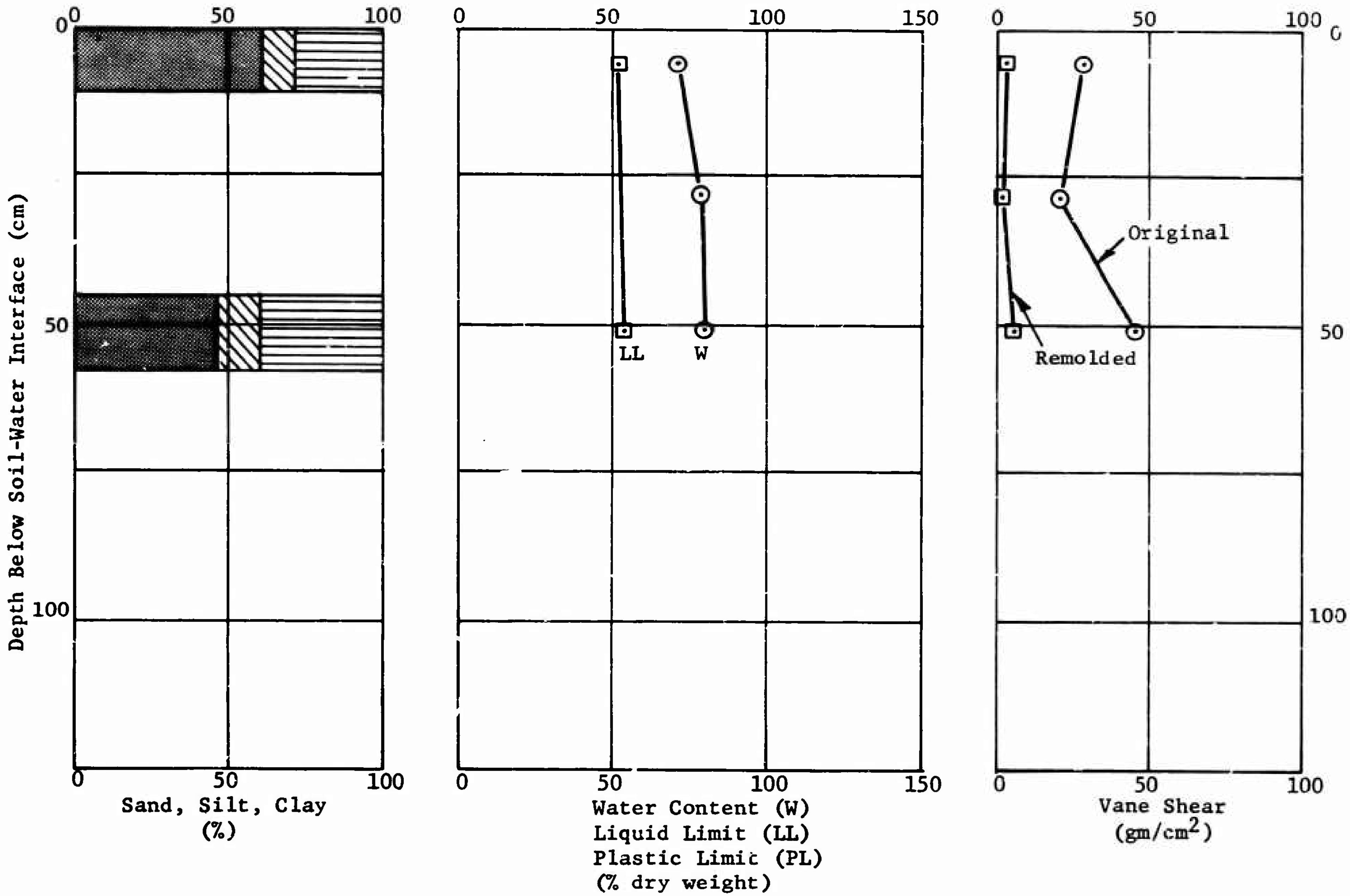

Figure 13. Soil parameters versus depth for Station I4.

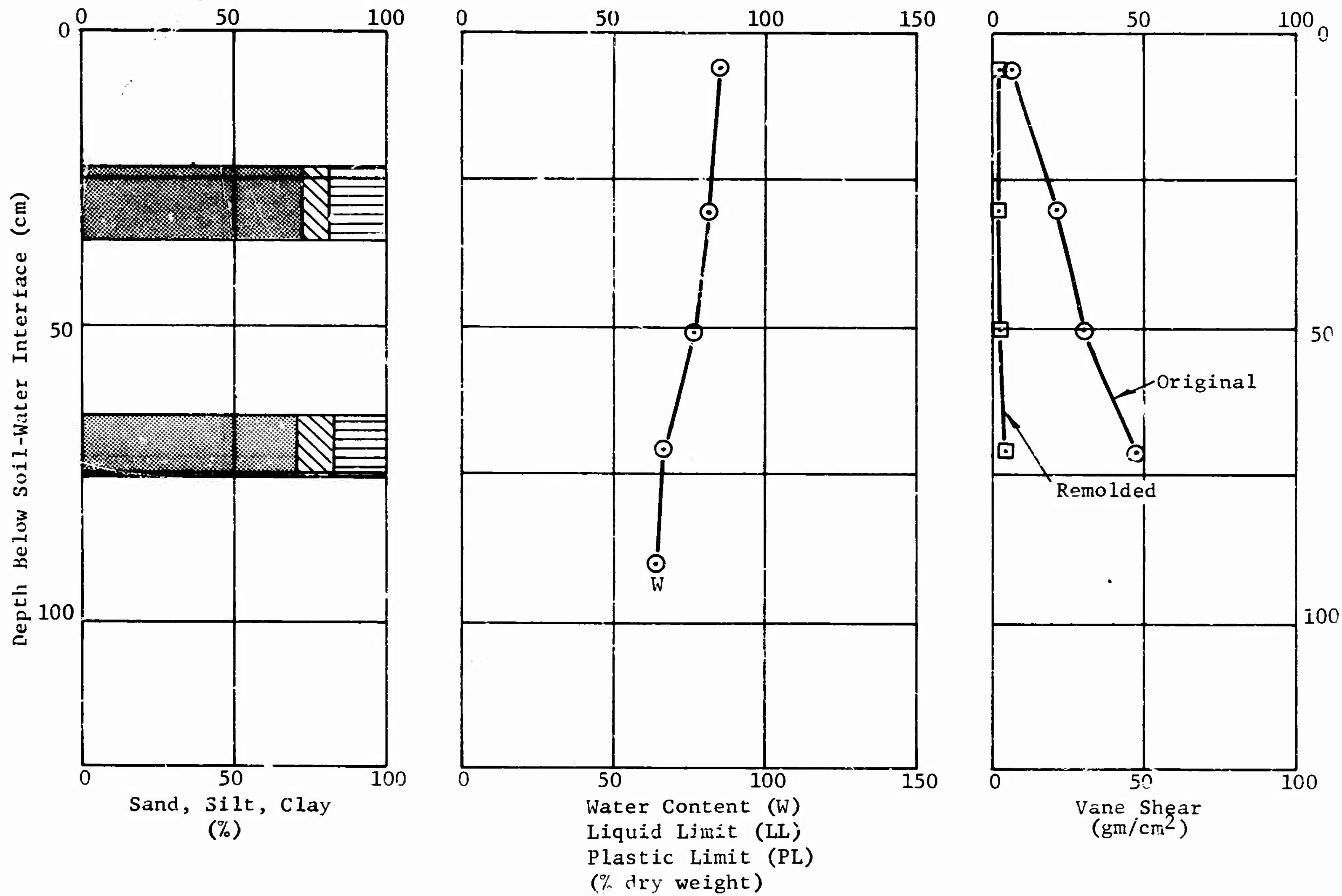

Figure 14. Soil parameters versus depth for Station J.

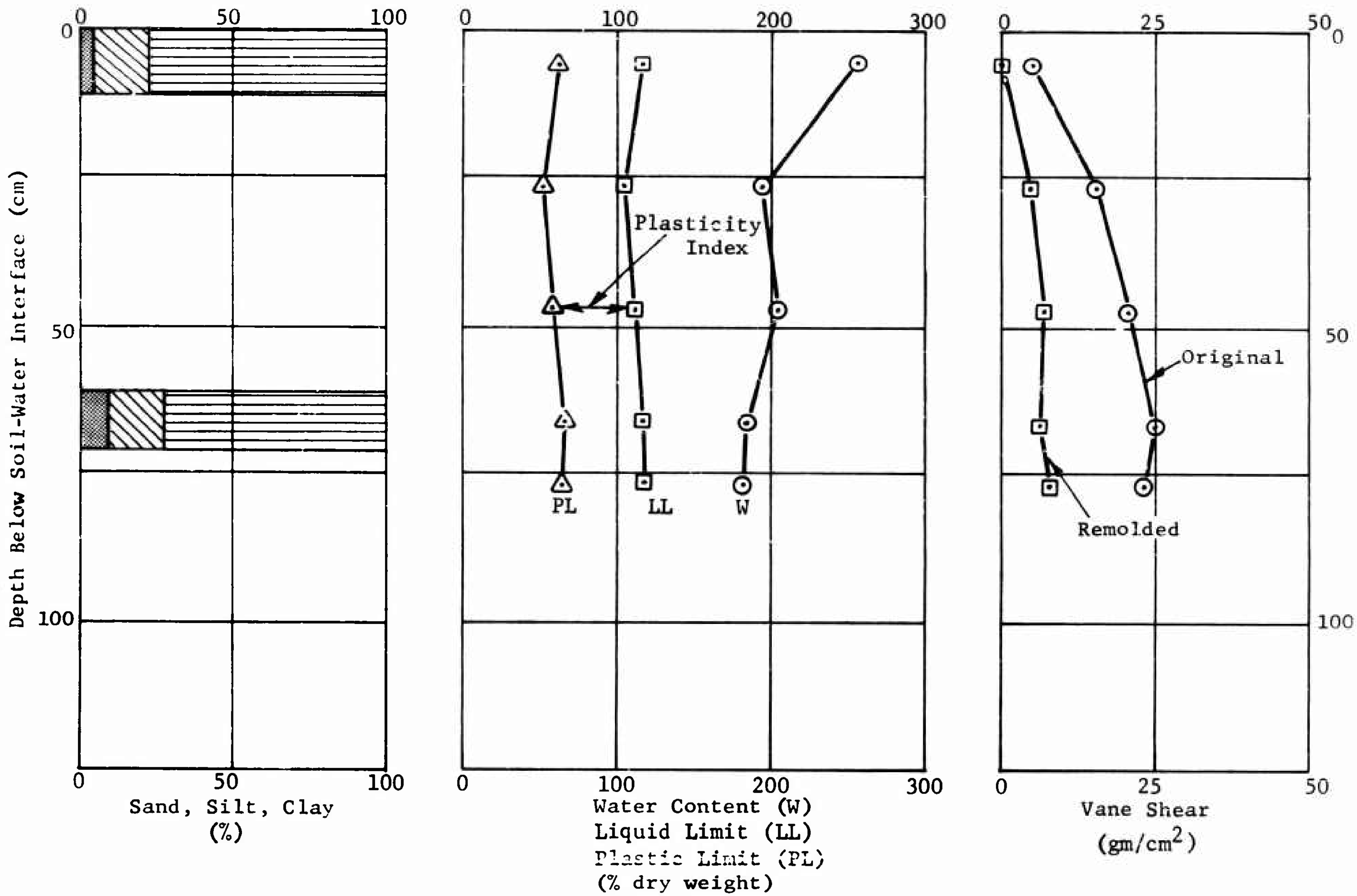

Figure 15. Soil parameters versus depth for Station K,

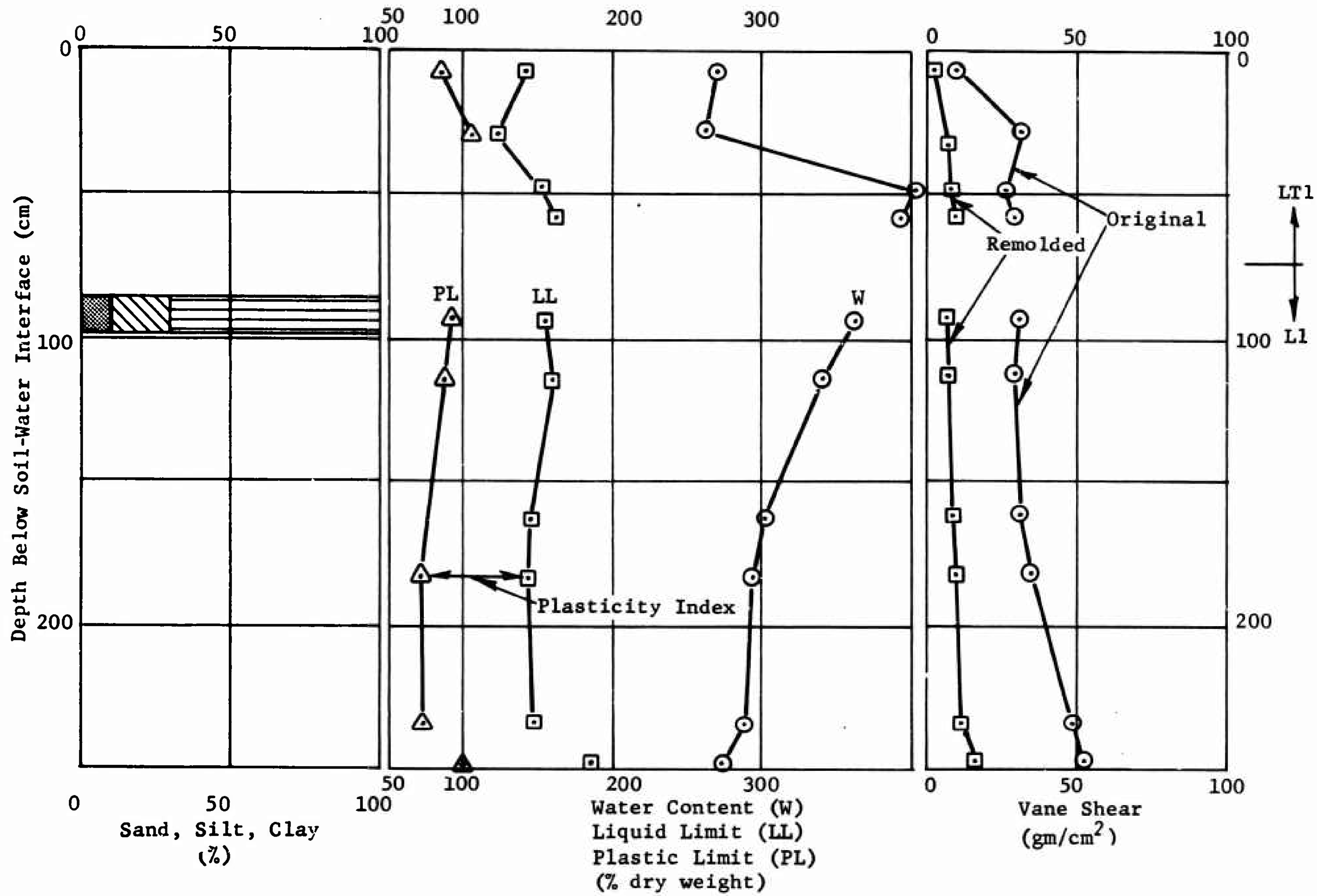

Figure 16. Soil parameters versus depth for Station L1 & LT1.

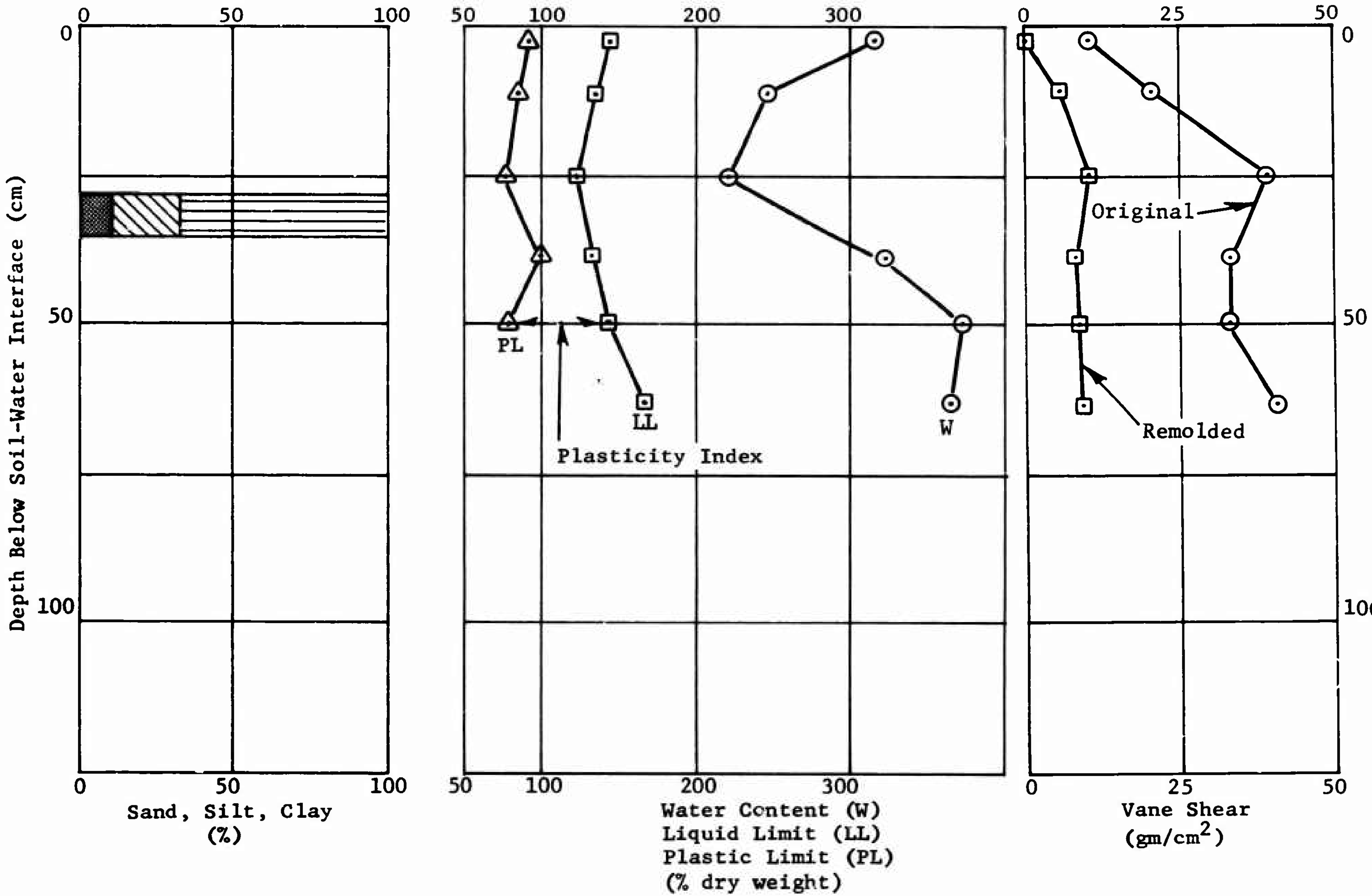

Figure 17. Soil parameters versus depth for Station LT2.

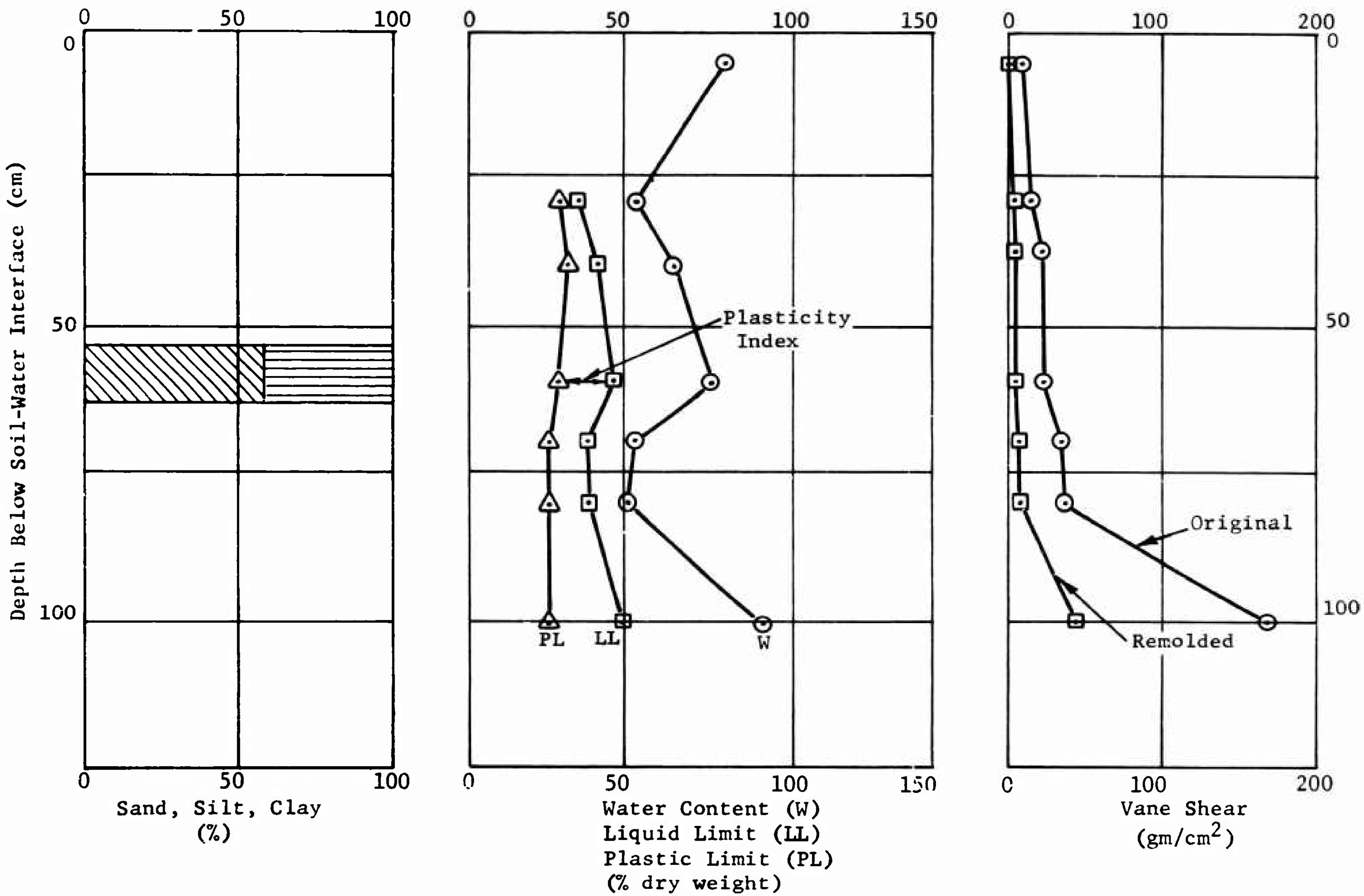

Figure 18. Soil parameters versus depth for Station M.

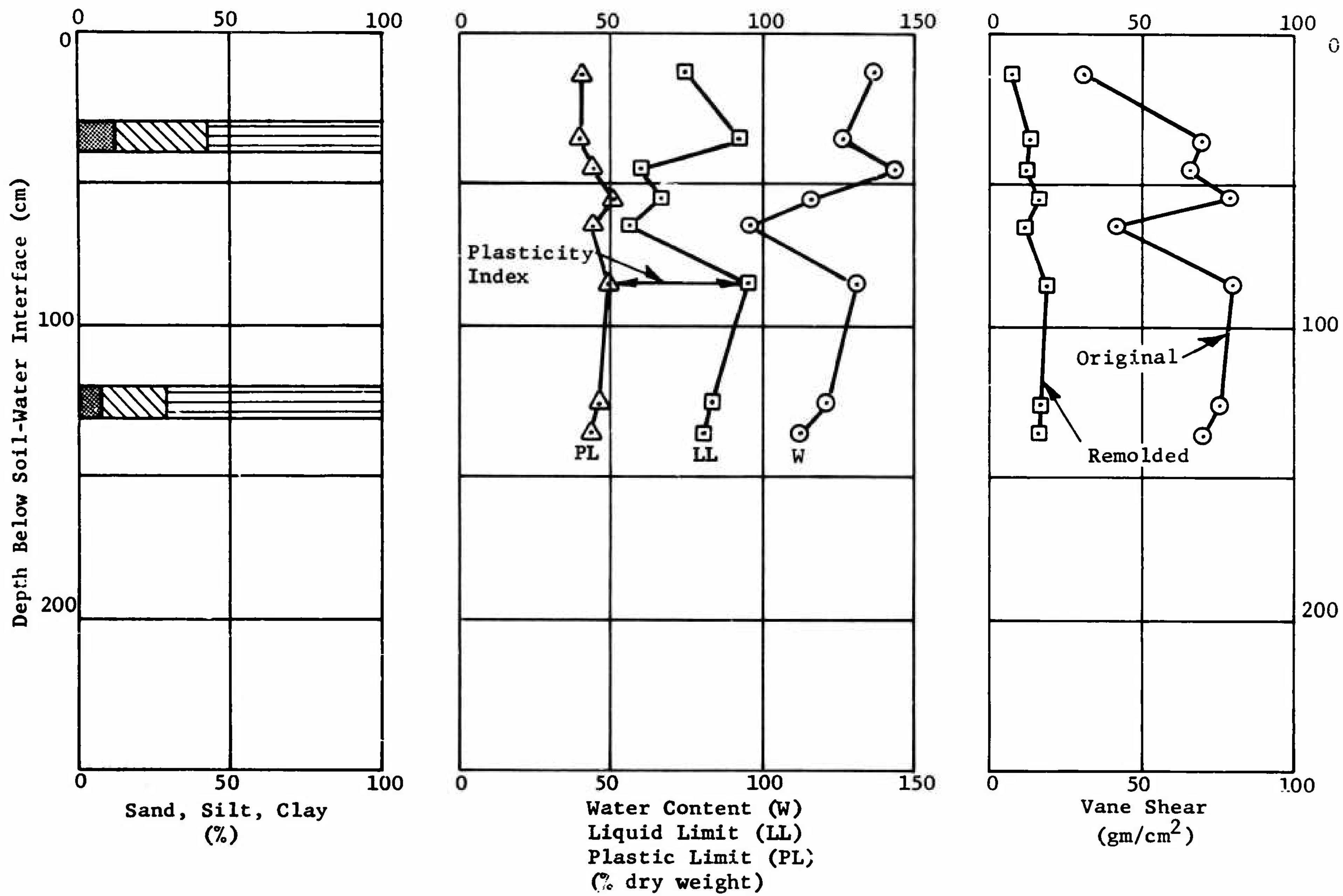

Figure 19. Soil parameters versus depth for Station N.

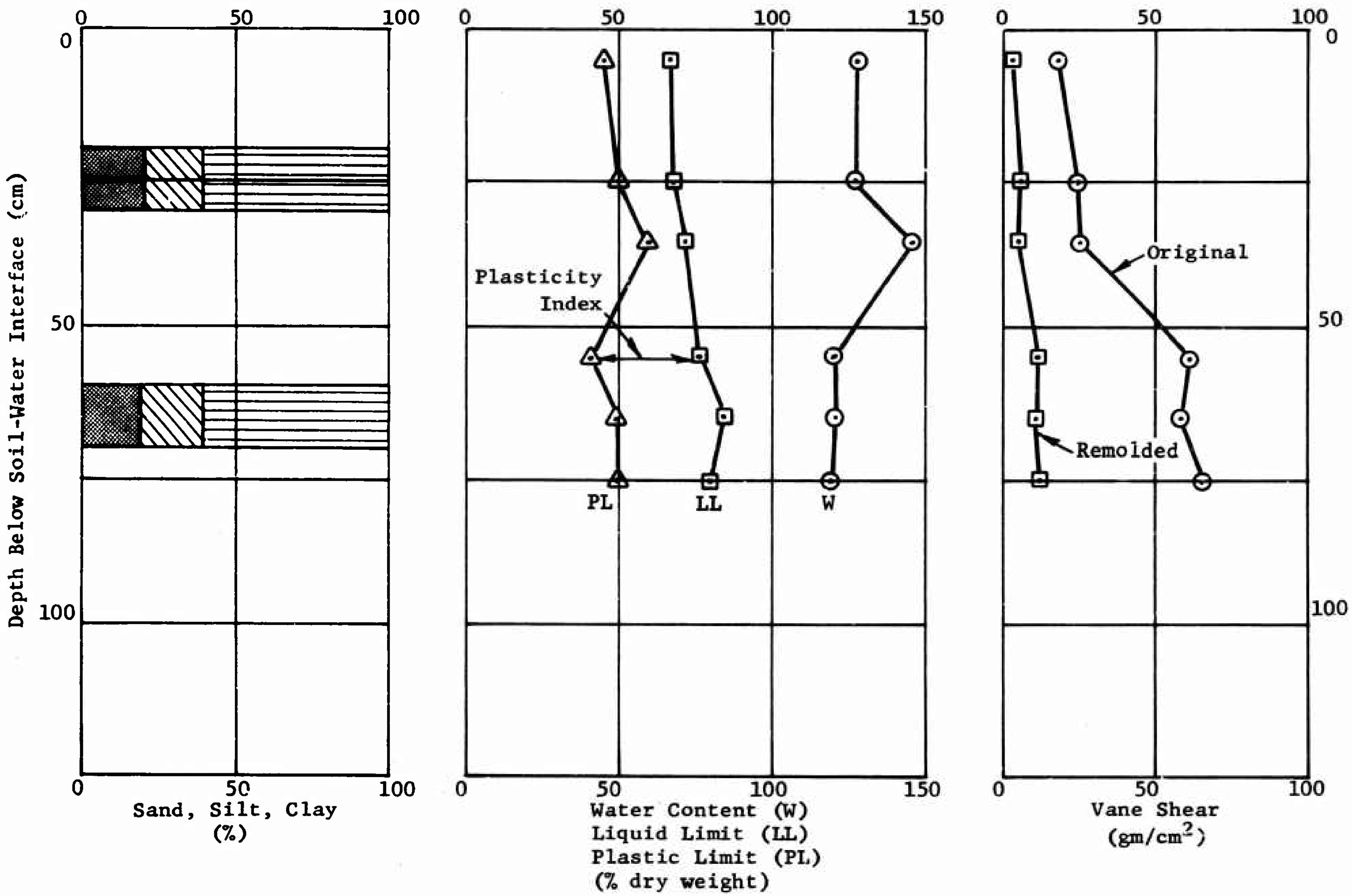

Figure 20. Soil parameters versus depth for Station O.

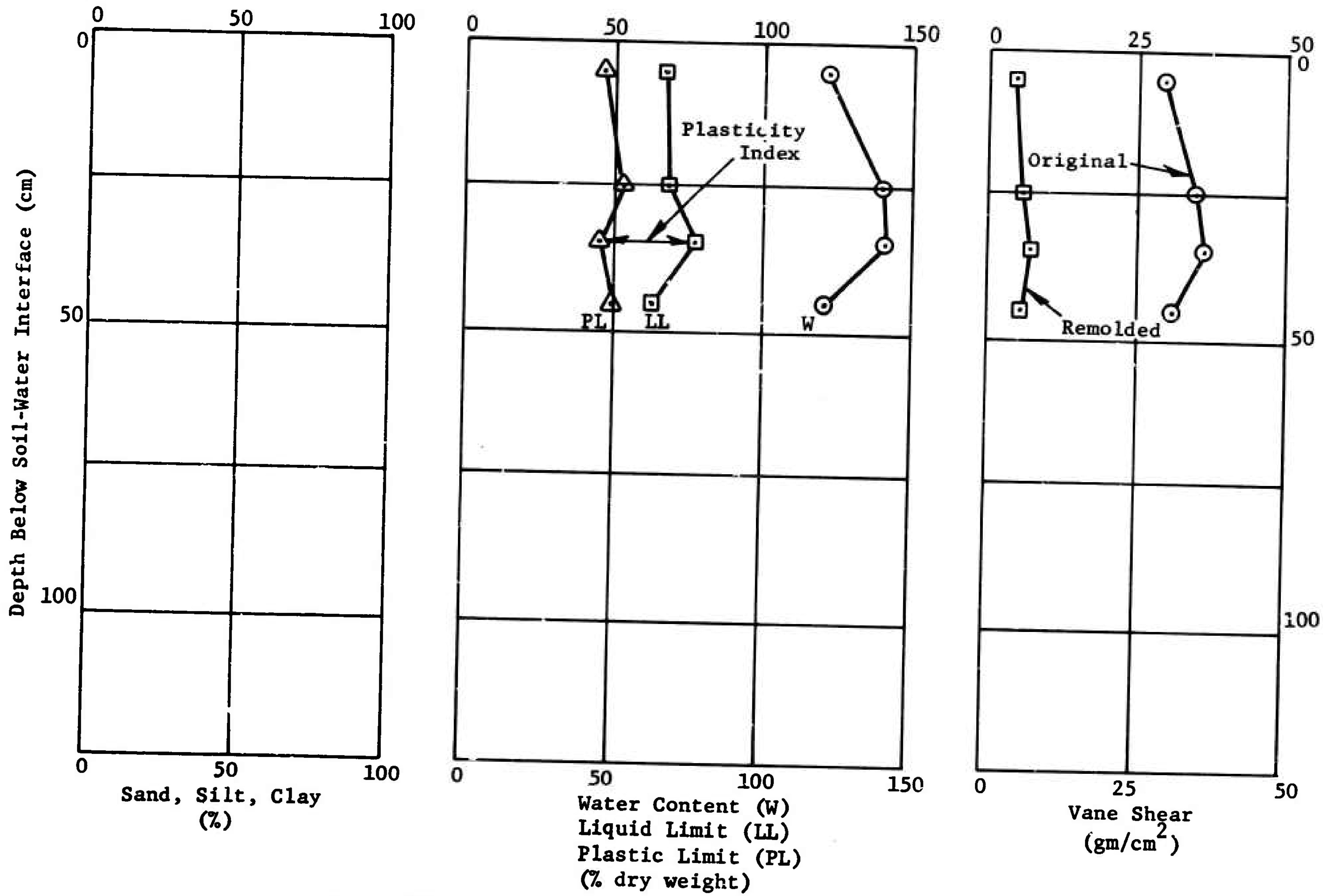

Figure 21. Soil parameters versus depth for Station OT.

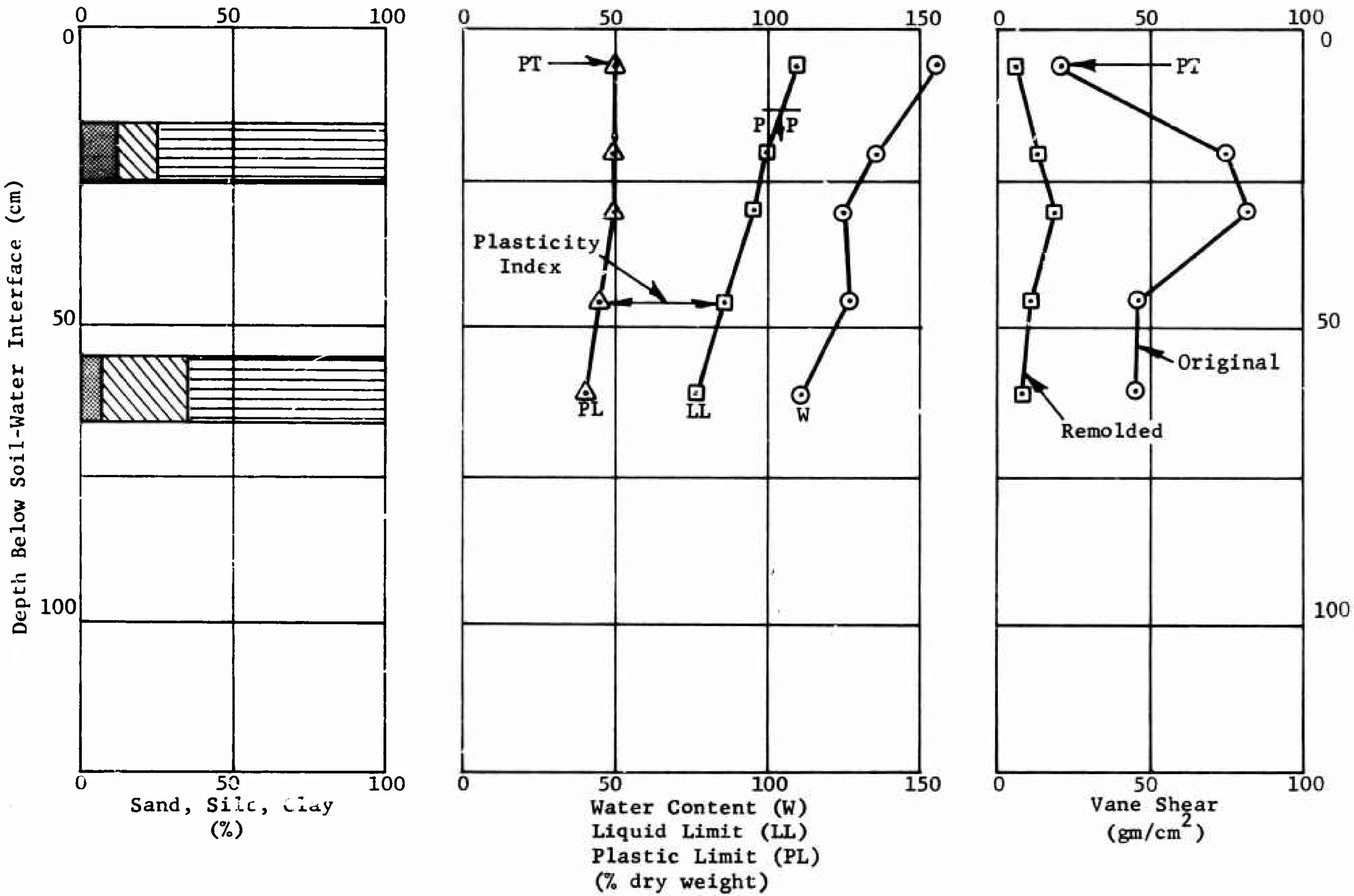

Figure 22. Soil parameters versus depth for Station P and PT.

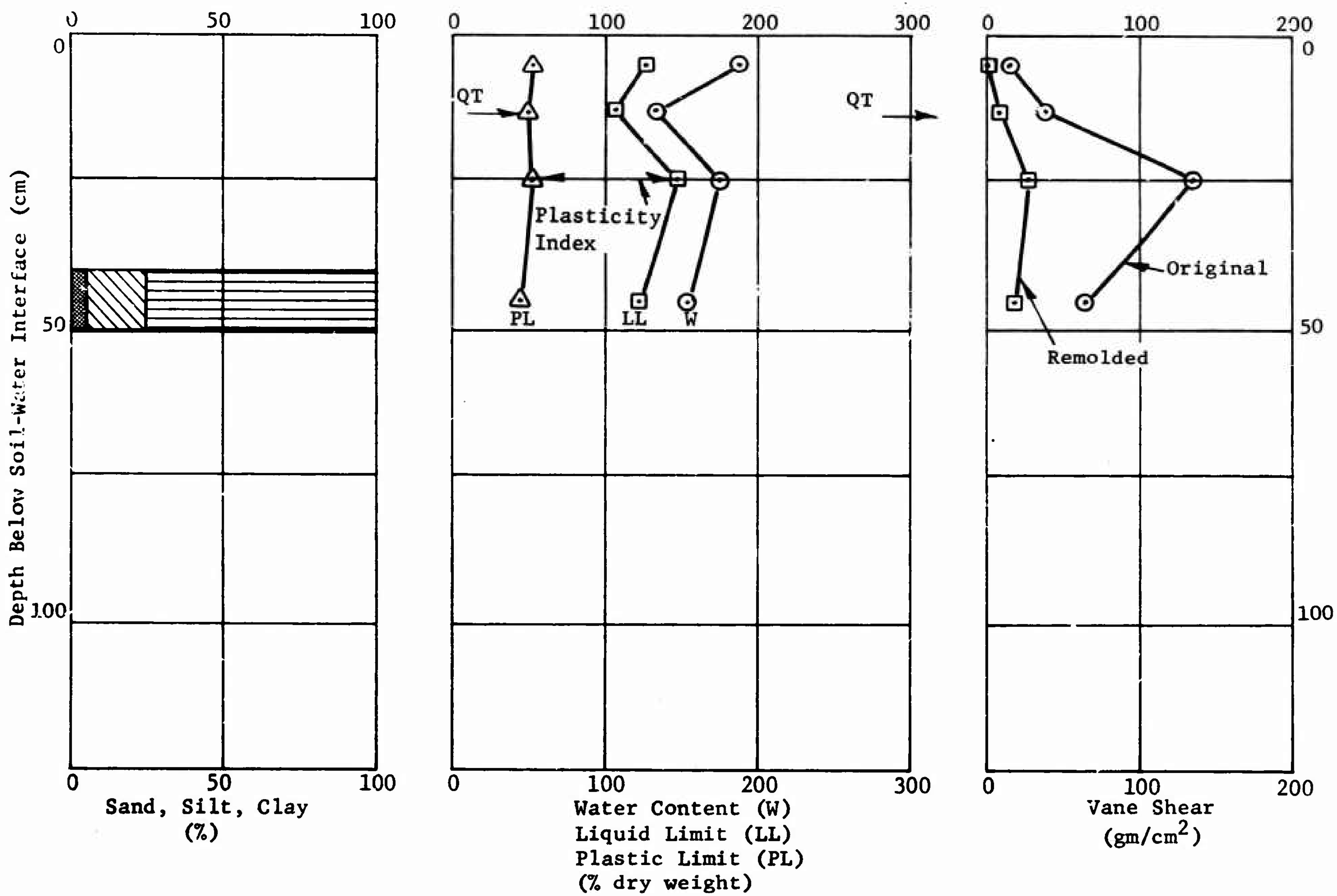

Figure 23. Soil parameters versus depth for Station Q.

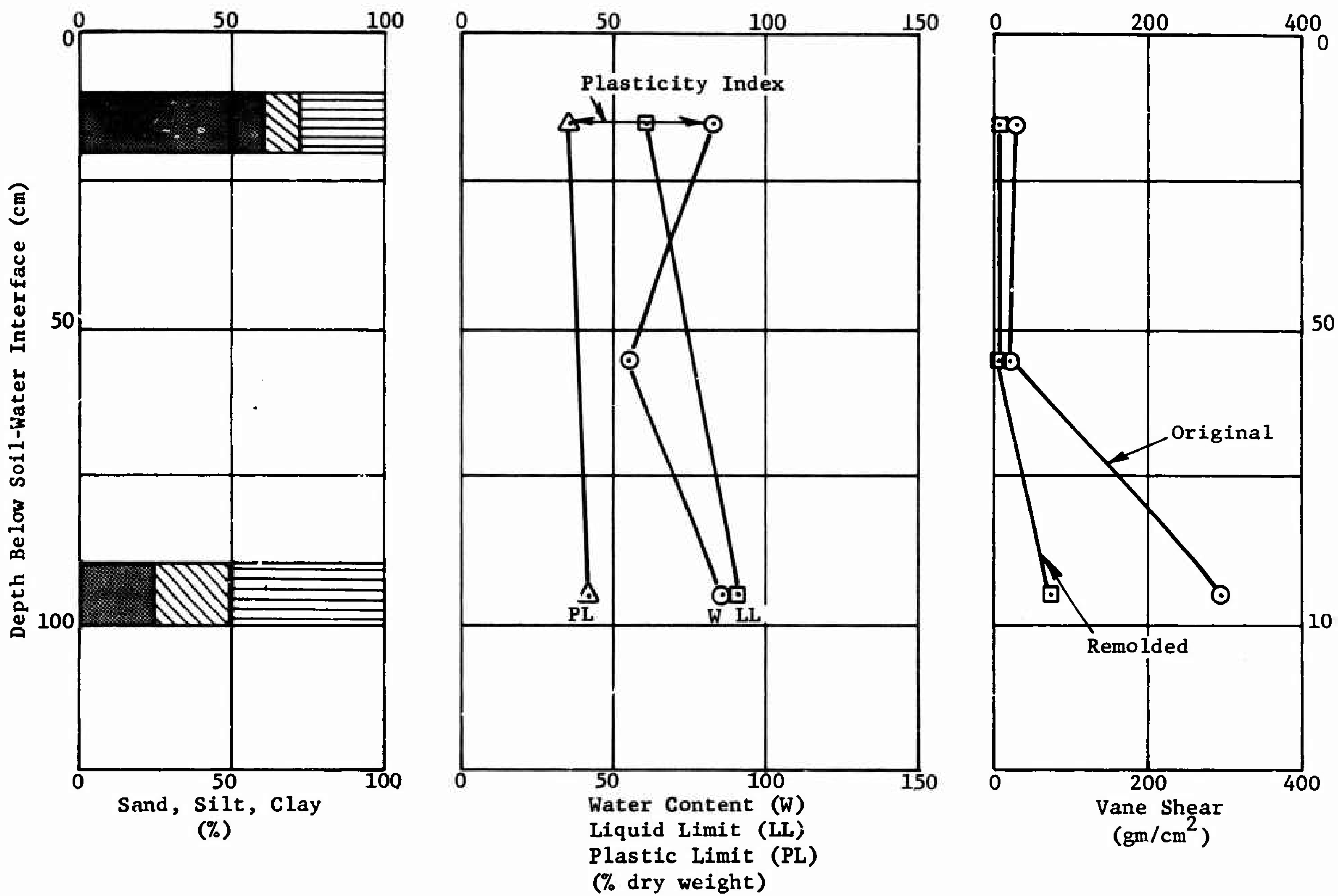

Figure 24. Soil parameters versus depth for Station R1.

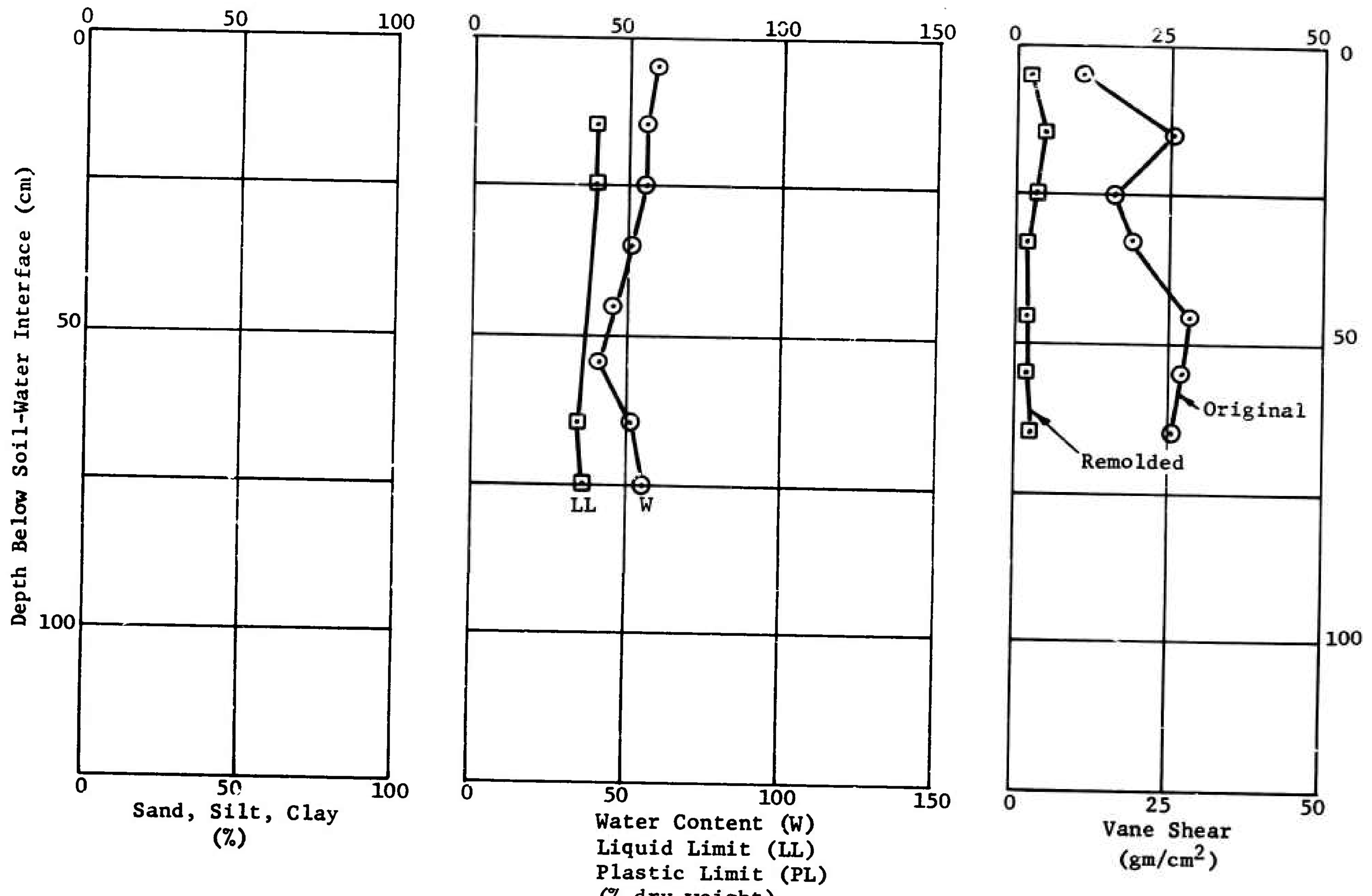

Figure 25. Soil parameters versus depth for Station R2.

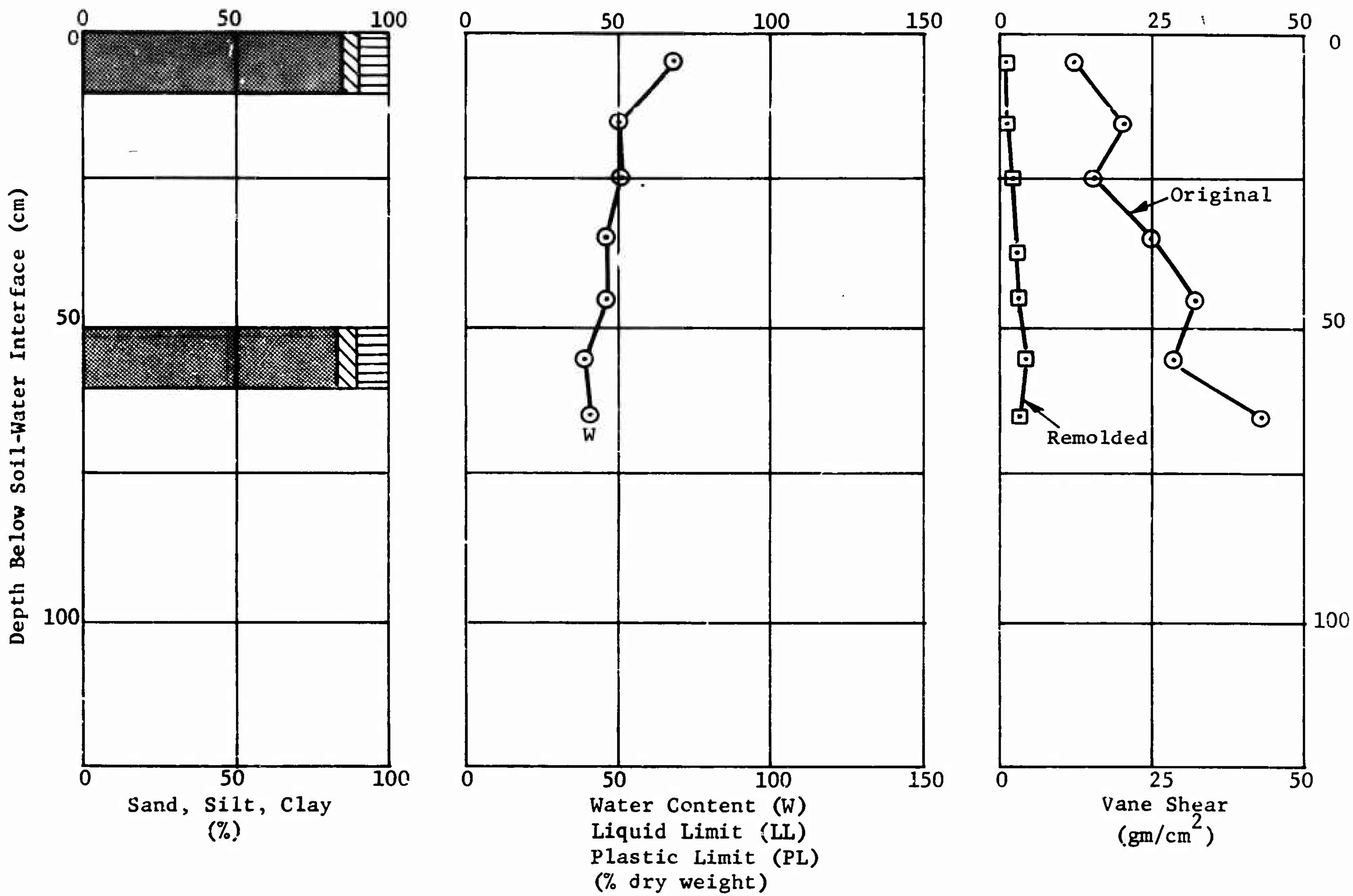

Figure 26. Soil parameters versus depth for Station R3.

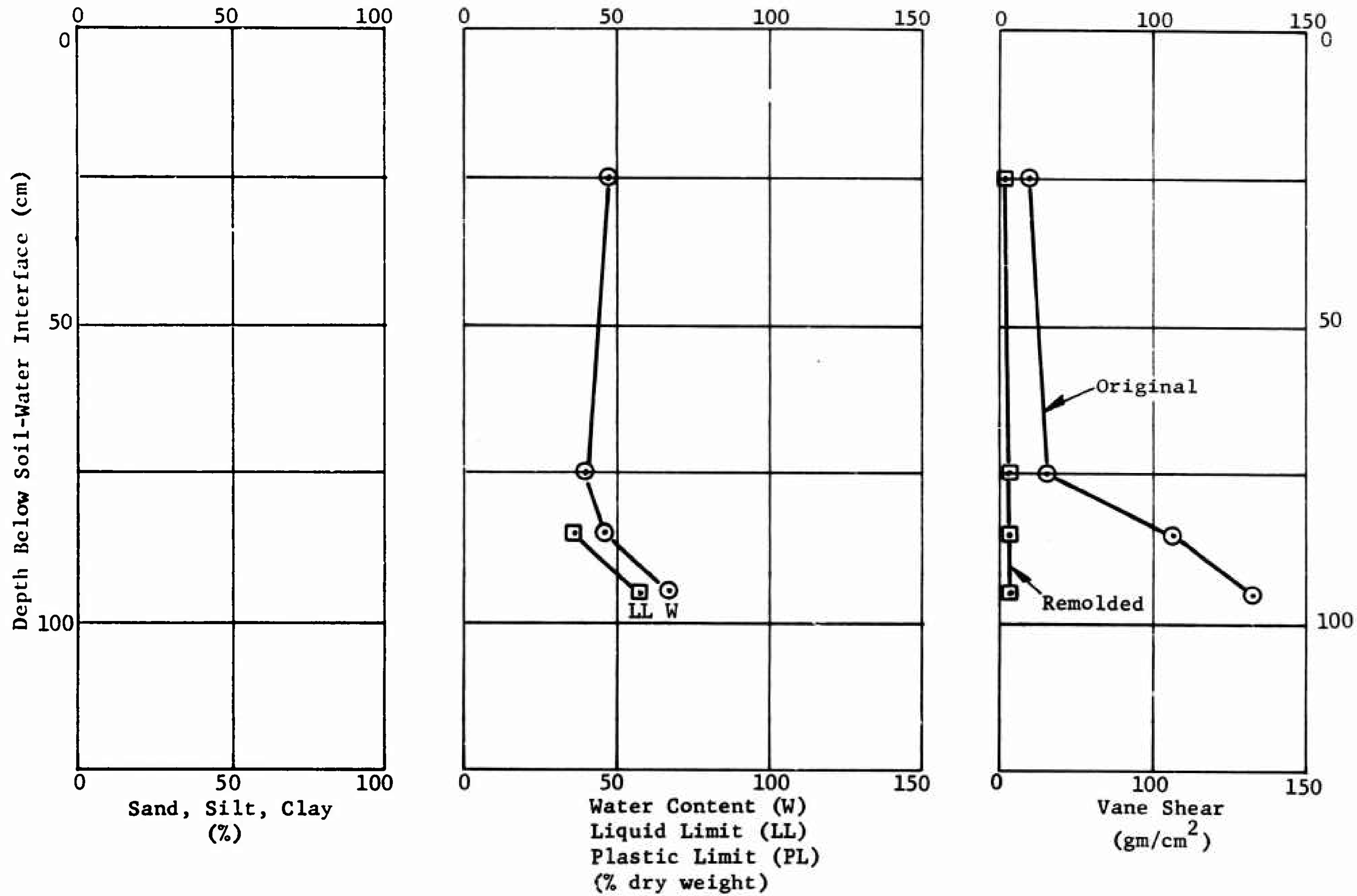

Figure 27. Soil parameters versus depth for Station R4.

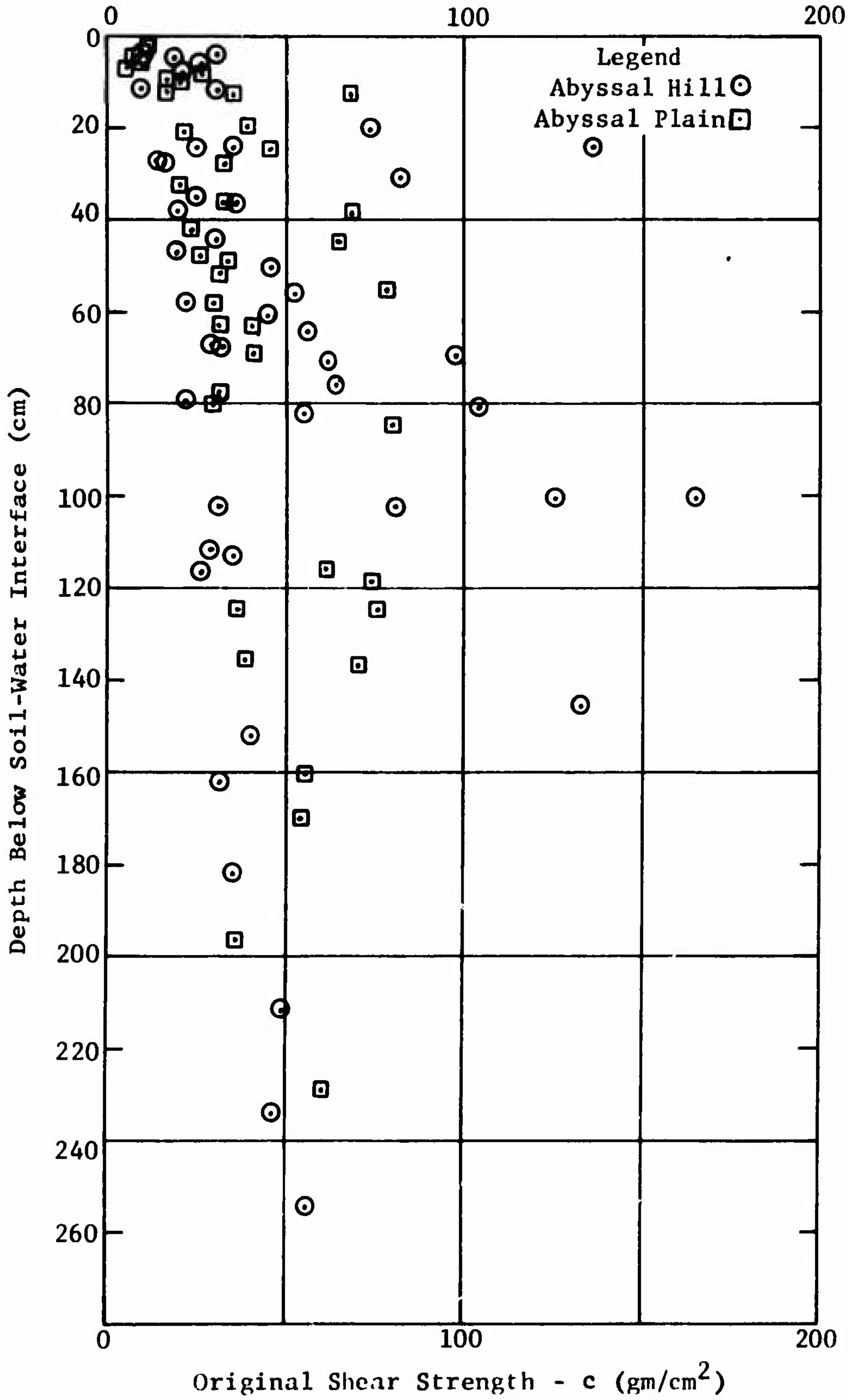

Figure 28. Original shear strength versus depth below soil-water interface.

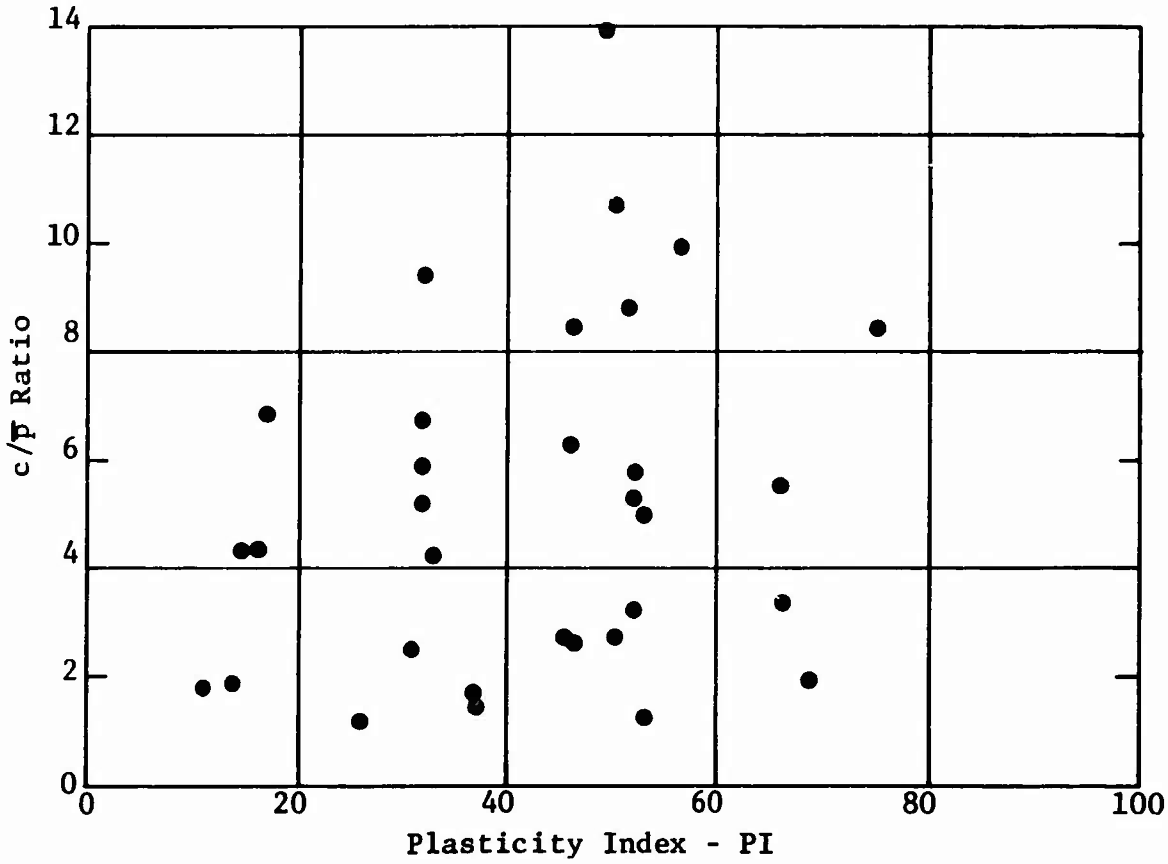

Figure 29. c/$\bar{p}$ ratio versus plasticity index for Abyssal Hill Province.

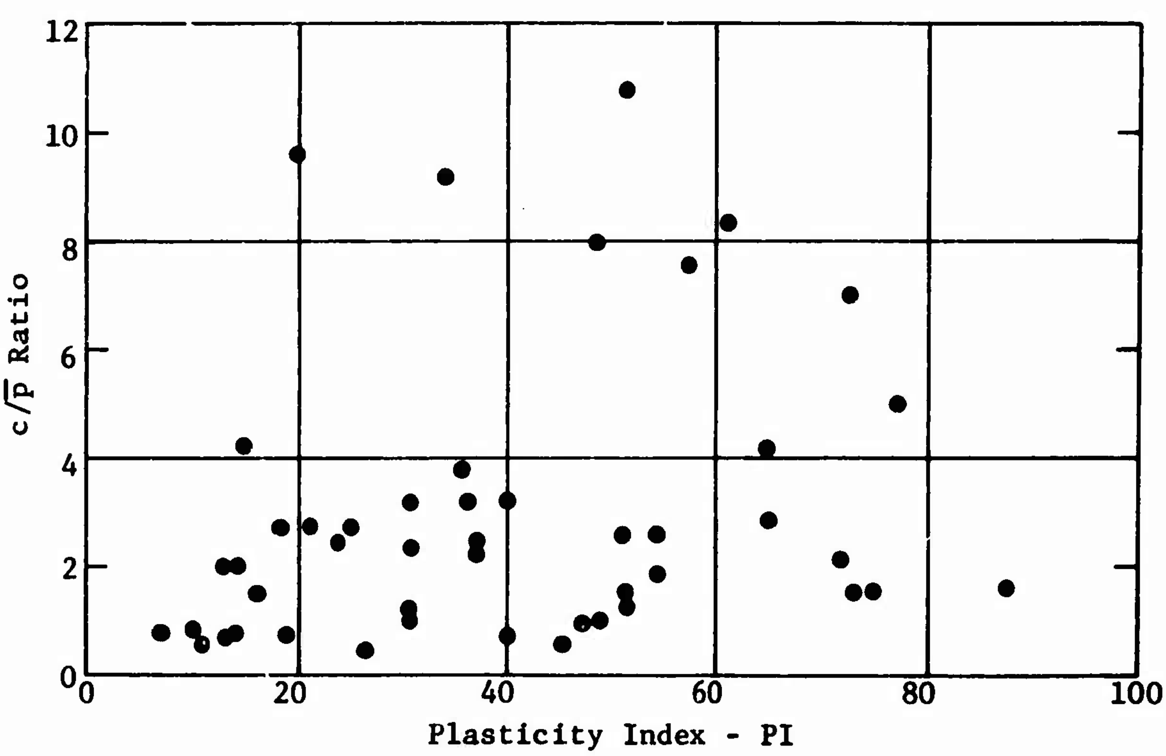

Figure 30. c/$\bar{p}$ ratio versus plasticity index for Abyssal Plain Province.

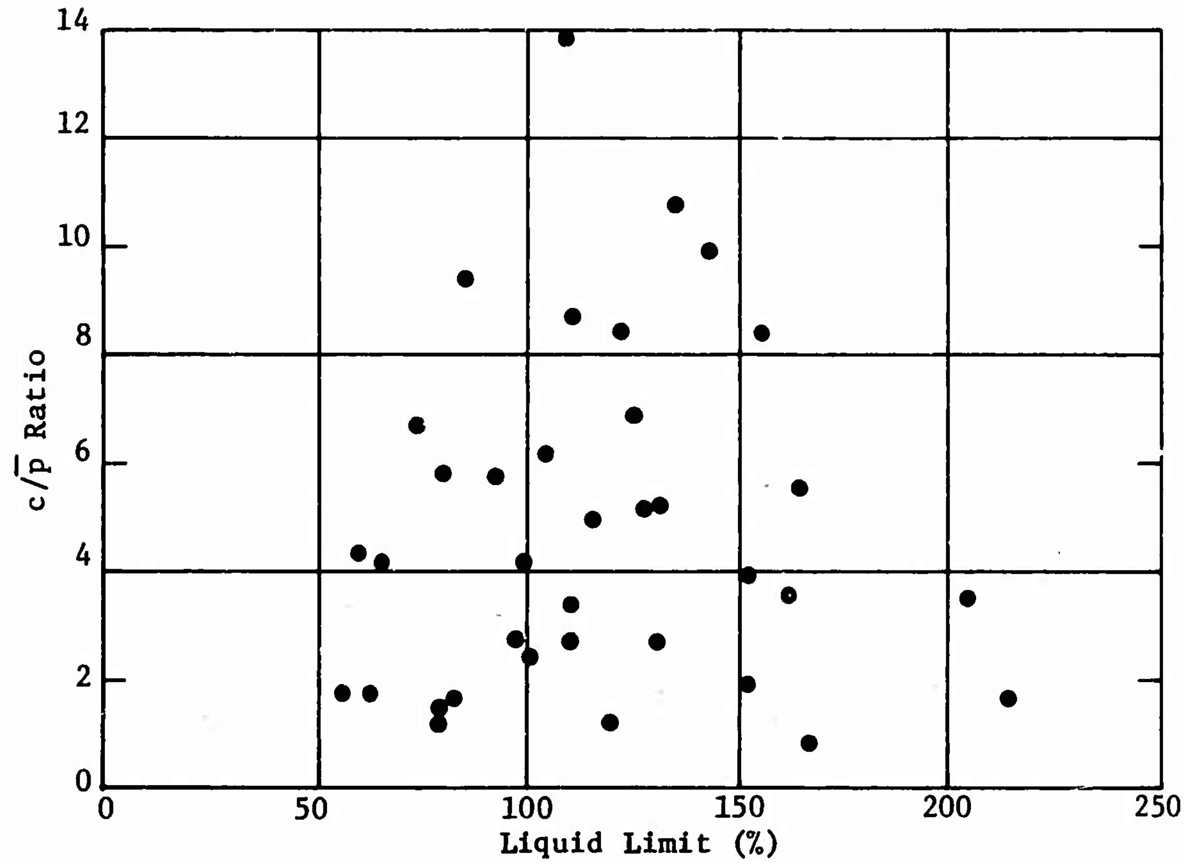

Figure 31. c/$\bar{p}$ ratio versus liquid limit for Abyssal Hill Province.

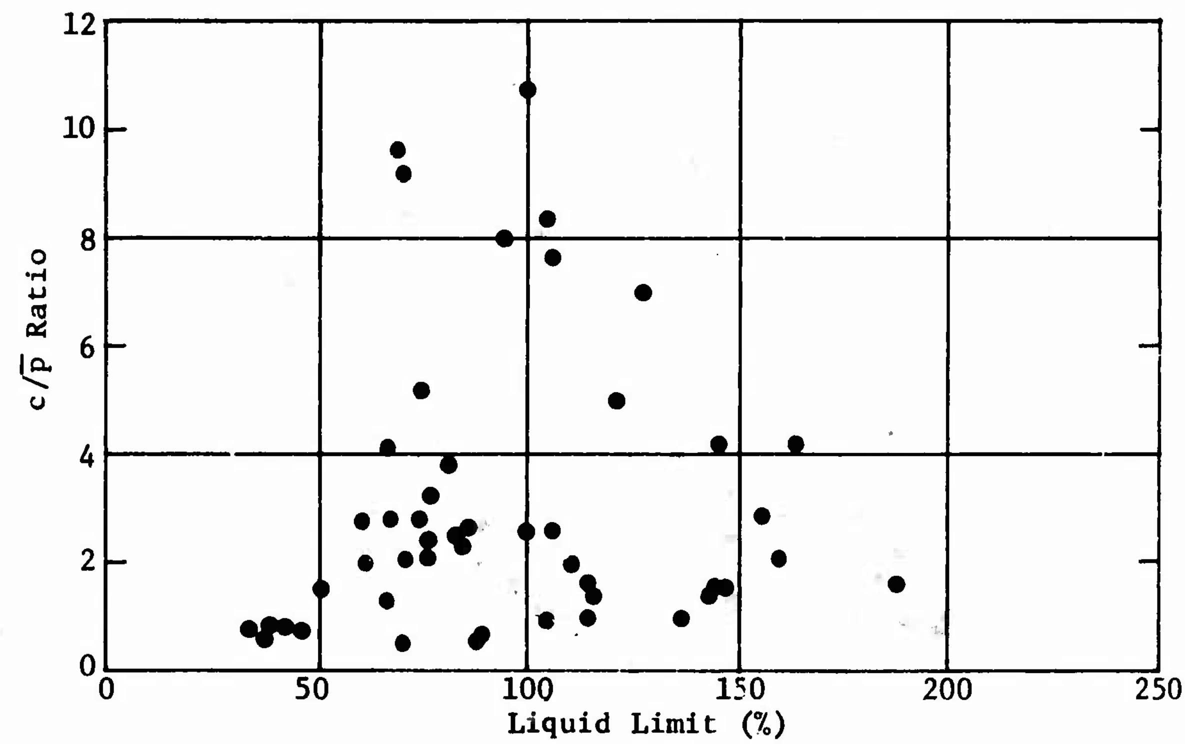

Figure 32. c/$\bar{p}$ ratio versus liquid limit for Abyssal Plain Province.

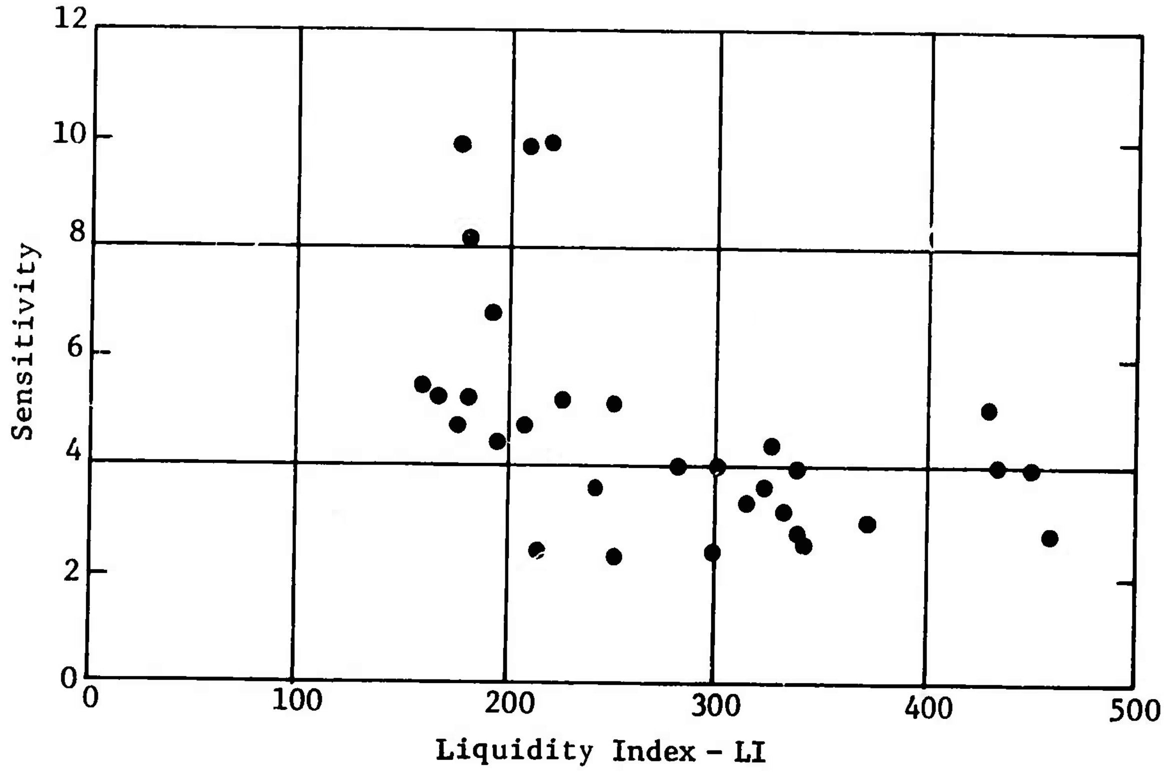

Figure 33. Sensitivity index versus liquidity index for Abyssal Hill Province.

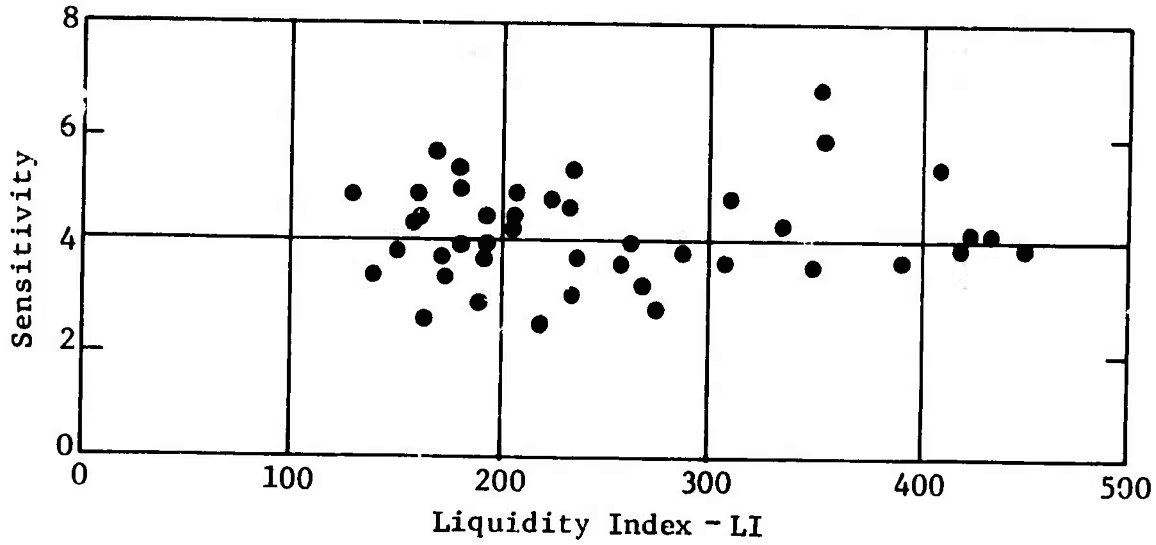

Figure 34. Sensitivity versus liquidity index for Abyssal Plain Province.

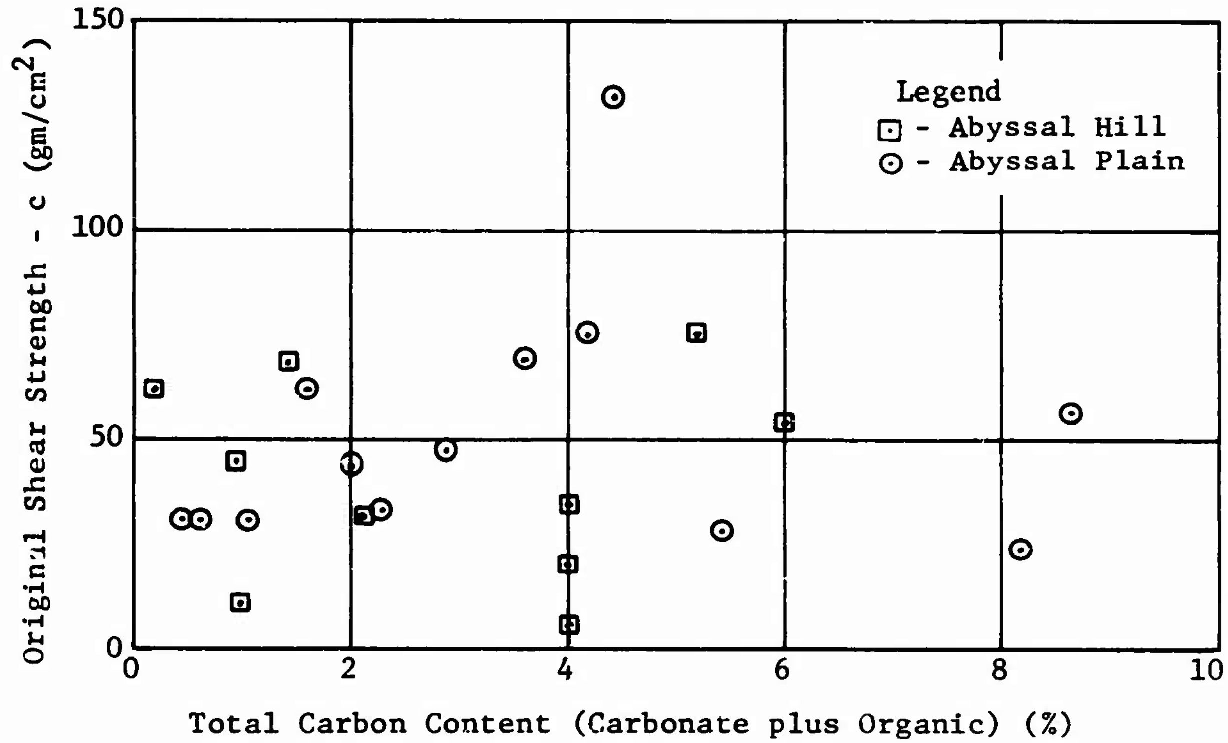

Figure 35. Original shear strength versus total carbon content.

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LIST OF SYMBOLS

A_r	Area ratio
BD	Corer barrel diameter
C_I	Inside clearance ratio of corer
C_O	Outside clearance ratio of corer
c	Undrained shear strength ($c \approx S$)
$c/\bar{p}$	Ratio of undrained shear strength to effective overburden pressure
D	Vane diameter
e	Void ratio
G_s	Specific gravity of particles
H	Vane height
ID	Inner diameter of corer cutting head
LD	Corer liner diameter
LI	Liquidity index
LL	Liquid limit
n	Number of blows to close groove in standard liquid limit device
OD	Outer diameter of corer cutting head
PI	Plasticity index
PL	Plastic limit
$\bar{p}$	Effective overburden pressure
S	Vane shear strength ($S \approx c$)
S_H	Shear strength on horizontal surface
S_R	Ratio of measured vane strength of actual undrained strength

S_V	Shear strength on vertical surface
T_F	Failure torque
W	Water content
w_n	Water content of soil which closes in n blows in standard liquid limit device
γ	Wet unit weight
ϕ	Angle of shear resistance